Increased Versatility of Modular Robots through Layered Heterogeneity

Larsen, Jørgen Christian; Støy, Kasper; Garcia, Ricardo Franco Mendoza

Publication date: 2010

Document version: Submitted manuscript

Citation for published version (APA):
Increased Versatility of Modular Robots through Layered Heterogeneity

Jorgen Christian Larsen, Ricardo Franco Mendoza Garcia, Kasper Stoy
Maersk Mc-Kinney Moller Institute
University of Southern Denmark
Email: [jcla, rfmg, kaspers]@mmmi.sdu.dk

Abstract—This paper introduces a new class of modular robots, called: “layered heterogeneous modular robots”, which is a type of modular robot, where the functionality of a robot is modularized into three layers of heterogeneous modules: mechanics, actuation and electronics. This novel approach may make it possible to create dynamic, power-efficient and robust locomotive modular robots, extending the usability of modular robots. Early tests show that the system is able to perform dynamic locomotion with speeds up to 11.8cm/sec with a specific resistance of 9.65. Also static structures have been constructed, forming a tower that is able to withstand a load of 29 times its own weight placed on top of the tower, without any power consumption. These tests show that the system is comparable in performance to those of non-modular robots.

I. INTRO

In robotics there is a special field called “Reconfigurable Modular Robotic Systems”. This field has been inspired by the way nature is built at a cellular level. In nature, complex organisms like mammals contain billions of cells, but only a few hundred different types of cells are found among them. These few hundreds of different cells are the basis of all living creatures. This idea of having a building set, only containing a few hundred different elements, is very interesting to the robotic science field, because it opens a new way to create robots. A way where robots are made from a number of smaller robots which together form the desired robotic structure. In robotics, this approach is called “Reconfigurable Modular Robotic Systems” and has been a field of research for the past 25 years [1]. As opposed to ordinary robots, where a robot is built for one purpose only and is a rigid structure, a modular robot is built from many smaller homogeneous or heterogeneous robots, where each module carries its own power supply, processing, actuation and connection mechanisms in order to connect to other modules. The modular robot can then change its shape into different morphologies dependent on the task the robot has to accomplish, e.g a snake in order to crawl through a hole, or a walker to travel great distances with high speed. Basically, all these tasks are accomplished with the same set of modules, just configured in different ways. The versatility of such systems gives some advantages over conventional robots known as the three promises of modular robots [4]:

- **Versatility:** The possibility of using each module in many different configurations gives the system a high degree of versatility.
- **Robustness:** Ordinary robots are very vulnerable to damages on the robot. Only one failing sensor could cause the entire robot to fail working. In modular robots this problem is much smaller because of redundancy. If a module breaks it can easily be replaced by another, even during run-time.
- **Low cost:** As modular robotic systems are composed of homogeneous modules, or a few heterogeneous modules, the modules can be mass-produced.

In the ideal world this would be a perfect solution to the problem of how to create cheap and versatile robots, but the past has shown us that in reality it is not as easy as it may seem. The problems that this vision also holds are the following:

**Problems 1 (Self-sustainability):** Due to the fact that all modules should be self-contained in order to function as individual small robots forming a bigger structure, all modules will have to contain electronics, batteries, actuation etc. This gives a great overhead in terms of size, weight and power consumption. Some modules in a structure may never even move; they are just part of the structure, carrying the weight of their actuators, and consuming the power necessary to keep the module running in standby mode.

**Problems 2 (Granularity):** When constructing modular robots, each module should be as small as possible to make it feasible to construct gripping mechanisms, tools, etc. from them. This however has proved to be one of the biggest challenges of all, because the technology for doing that is not yet here. The smallest modules that are self-contained, are still in the 5-10 cm range or bigger, making it impossible to create such structures. The technology will have to facilitate production of a complete module in the millimeter scale or nanometer scale for that to be possible. This is a limiting factor to the versatility of the modules.

**Problems 3 (Performance):** Modular robots have shown that they are capable of doing various tasks, with different configuration, which is one of the promises of modular robots. However, in order to make modular robots competitive to ordinary robots, the performance of the different tasks that modular robots can do will have to be improved in terms of speed, energy efficiency and reliability.

The problems stated in problem 1-3 are the most limiting ones that modular robots are facing today. In order to solve those, we have formed the following hypotheses.
Hypothesis 1 (Increase heterogeneity): The problem of having an overhead is biggest when dealing with homogeneous modular robots, but does still exist, to some degree, in heterogeneous modular robots as well. To overcome this problem, the degree of heterogeneity must be reevaluated in order to create even more specialized modules, where the complexity in each module is reduced to a minimum. By doing that the overhead in terms of electronics and mechanics can be minimized drastically.

Hypothesis 2 (Reduce complexity of modules): As the complexity of the modules rises, so does the size. Therefore it will help to decrease the complexity of the modules, and create more specialized modules in order to make each individual module smaller.

Hypothesis 3 (Narrow area of application): The diversity of tasks that a modular robot can do is huge, so in order not to get lost in trying to increase the performance of modular robots in all of their areas, this paper will focus on one specific task, namely legged locomotion, and try to make modular robots better in terms of embodiment, including robustness, energy efficiency and adaptation.

Based on the hypotheses stated above, this paper describes a new way of designing modular robots by introducing a new class of modular robots, called “layered heterogeneous modular robots”.

II. RELATED WORK

Modular robots have been around for the past 25 years, and a variety of different types of modular robots have been developed in this period. This paper will mainly relate to chain-based modular systems such as CONRO by Shen et al. [2], CKBot by Yim et al., SuperBot by Shen et al. [3], Topobo by Raffel et al. [5] and PolyBot by Yim et al. [6]. Common for these systems is the fact that they mainly have been developed with some sort of locomotion in mind, either snake-like locomotion or by walking on either two, four or six legs. All of them have shown locomotion capabilities in different configurations, and thereby demonstrated that nature’s principle of having a few different building blocks to create a variety of different structures also makes sense in the world of robotics.

Another category that is worth studying is construction kits, aimed at children as toys. The reason why it makes sense to look at this category is that such kits consist of different components (rods, joints, motors etc.) like in modular robots, and that each kit contains a large number of different elements, which increases the number of construction possibilities. The construction-kit category embraces many different kits, but the following have had the main focus of this project: Erector [11] by Gilbert [12], Meccano [13] by Hornby [14] and LEGO [15] by Kristensen [16]. These three kits make it possible to build different kinds of legged locomotive creatures, perhaps even in a bigger variety than in the ones mentioned above, possibly because of the large number of building blocks available.

Modular robots have shown locomotive capabilities with different configurations, where gaits from animals have been implemented, thus showing the potential of modular robots as elements of a walking structure. Construction kits, on the other hand, have a unique ability to form static structures with great strength from only a few simple components. What we want to do is to combine the abilities of the two systems mentioned above to form a new breed of layered heterogeneous modular robots focused on locomotion.

III. DESIGN

Modular robots face a number of problems, which are (1) the overhead in terms of electronic, actuation and structure, (2) the granularity and (3) the performance in terms of speed, energy efficiency and reliability, as stated in section I. A number of different attempts have been made over the years to create a system that can solve these problems. This section will present the ideas and visions behind a novel layered heterogeneous modular robotic system called LocoKit. Our motivation for creating a new modular robotic system comes from an interest in studying the interaction between morphology and locomotion. More specifically, we plan to address the following three areas:

- **Different morphologies**: The system should facilitate the possibility to study different morphologies, and to see how changes influence the locomotive abilities.
- **Adaptivity through morphosis**: On top of locomotion, the system should also be capable of doing voluntary and involuntary mophosis in run-time. This could be like changing gait parameters while moving on different surfaces, or to adapt if a leg falls off or becomes useless. These adaptive features should not be implemented in control only, but also as part of the structure.
- **Dynamic locomotion**: To perform locomotion, which is energy efficient, dynamic and adaptive, the system should be interacting with its surroundings, like in nature where the animals adapt their gait pattern to the environment.

Common to all previous modular systems is the fact that they have all proved that the concept of modularity works, and produces results in terms of different kinds of locomotion either as walking or crawling gaits. However, they are still limited by the problems stated in section I. The difference we want to make in the creation of this new system is stated in table I. What is seen from the table is that LocoKit is combining features from both of the other two categories in order to gain what is best from them to fulfill our needs. The area of self-reconfigurable modular robots, has not been discussed until now. A modular robot of this category can change its own shape from e.g. a walker to a snake if it finds this kind of locomotion more appropriate for its current conditions. However, this ability requires the modules to be highly homogeneous in order for the robot to self-reconfigure, which is why this category cannot currently be
combined with our design, because the overhead in terms of electronic, actuation and structure is too huge for our purpose.

A. Modules in the system

Locomotion in robots can in general be split into three groups, namely structure, actuation and electronics. The structural parts are needed to build the skeleton of the desired robot. This could be a robot for legged, jumping, crawling or sidewinding locomotion. When the skeleton is built with its links, joints, and rods some actuation will be needed in order to make it move. With the skeleton and actuation in place, the only thing missing is the electronics, which together with sensors will control all the actuators on the robot and make it walk, run or jump. The following will describe the first iteration in the creation of the new layered heterogeneous modular robot, LocoKit, guided by the hypotheses in section I.

1) Structural parts: To form the skeleton of the robot, a number of small passive building blocks have been created. As opposed to many other modular robots, this system does not form rigid structures, but instead structures that allow for some flexibility. This is controversial, opposed to other systems, where a stiff structure is desirable in order for the system to align its modules for self-reconfiguration, but since this system is only reconfigurable, it is seen as an advantage, because it allows us to create dynamic structures for dynamic locomotion, as is one of our requirements for this system. Figure 1 shows the three components used for structure creation in the system. As connection between joints in the structure, glass-fiber enhanced plastic rods have been used. These are seen in e.g. figure 1(c). This type of rod was selected because of its flexibility and strength. Figure 1(a) shows a freely rotary joint that links two rods together. This joint also contains mounting points, where wires for actuation can be mounted. This joint is used when it is desirable to actuate the joint. In figure 1(b) a fixed joint is shown. This joint can be fixed in 12 different positions, and its primary use is to build the rigid part of the structure. All structural components are mounted firmly onto the rods with screws.

2) Actuation: Now with all the structural components in place, forming the structural basis of the robot, it will need some actuation in order to move. Actuation will have to be applied at the joints where it is needed, but opposed to placing actuators directly onto the joint, this project have been inspired by nature in its way of transferring power from the muscles and onto the joints. In LocoKit, actuation power are transferred from the actuators to the joints via wires. A principle that has been used in e.g. model airplanes, robot hands [17], we now introduce into modular robots.

The purpose of not placing the actuator directly at the joint is to minimize the weight and size of each construction module and to keep the weight of the actuators in the centre of the robot. It also allows for a greater control of the dynamics of the robot in terms of weight distribution, because we can place the actuators as desired because of the wires. Transferring the power from the motors onto the joints via wire systems, however, introduces friction to the system every time the wire is bent in some way and also makes each movement less precise. These problems will be addressed at a later point of time. Figure 2 shows configuration examples of the actuation.

3) Electronics: Normally, the structure, actuation and electronics would have been one module, but now it has been shown how structural parts and actuation can be split into separate layered modular systems. The same is true for the electronics, but the electronics has been further divided into separate modules, each representing different functions. This way of dividing the electronics makes it possible to use
the exact amount of electronics needed at specific places in
the robot, and thereby limiting the amount of electronics in
the robot. The electric boards have been made so that they
can be stacked to form a sandwich structure - see figure 3.
One board (the CPU board) is always required to be in the
sandwich, but depending on whether the sandwich should
be controlling actuation, sensors or just be a computation
unit, it can be configured accordingly. Having this sandwich
structure makes it easier to create new electronics for the
system. It simply just have to fit with a set of pin connections
and electronics specifications. In the future there will be
boards for communication, sensors and motor control. The
electronics for LocoKit is based on the electronics designed
for the ODIN modular robots [7].

IV. OBSERVATION / EXPERIMENTS

In this section we will present some experiments that
demonstrate the versatility of the LocoKit. Placed between
ordinary modular robots and construction toys for kids,
LocoKit has the capability of forming structures from both
of these worlds, as experiments will show. We will docu-
ment the following two configurations, (1)Quadruped walker,
(2)Static tower.

A. Quadruped walker

To demonstrate locomotion, a quadruped walker has been
constructed. The walker has been constructed in a way that
makes it possible to use only two motors to actuate four
legs. This approach will make the robot less heavy and more
power efficient, because the speed of the robot will not be
increased by the addition of another two motors, since the
step length is limited by the way motors are attached to the
legs. The control of the motors is implemented in a simple
manner where the motors are oscillating between two fixed
angles. Then by connecting the output from the motors, via
wire cables to the legs, the actuation power is transferred
from the motor onto the legs and thereby allowing the motors
to be kept in centre of the robot. The legs are attached in
pairs of two to the motors. One pair is the back legs, and
one is the front legs. The legs are coupled in anti-phase. To
create a gait, the two motors are oscillating with a phase
shift, and thereby creating a simple walking gait. The gait
was optimized based on the speed and specific resistance,
and measurements shows that the selected gait gave the
highest speed with the lowest specific resistance, which tells
us that the dynamics of the robot helps to improve the
performance - see figure 4(b). The speed of the walker was
measured to 11.8cm/sec with a specific resistance of 9.65.
The specific resistance \(\epsilon\) was calculated based on the total power consumption of the robot when walking, calculated by equation (1).

\[
\epsilon = \frac{E}{Mgd}
\]

(1)

The specific resistance in (1) is a dimensionless number. This equation is useful in the evaluation process of mobile robots because it makes it easier to compare performance between different robots. Here, “E” represents the total energy consumed when traveling a distance of “d”. The mass is “M” and the gravitation is “g”, [9]. It is, however, difficult to make a good comparison to other modular robots because very few have actually made such measurements. Measurements carried out by Sastra et al. [8] with a loop configuration are the only one available, but as the configuration is completely different a comparison would be meaningless, because the configuration makes the robot more efficient. To do a fair comparison to other modular robots, the configurations would have to be somewhat identical, e.g. a legged robot.

When comparing to other quadruped robots that are non-modular, LocoKit is not performing as well as them, which was also expected, because LocoKit is still at a very early state of its development. Most other quadruped walking robots have a specific resistance in the area of 1-10 [10]. However, tests show that LocoKit is able to produce locomotion like other modular robots, and has a performance that is comparable to that of other quadruped robot.

B. Static tower

In this configuration the components are forming a simple tower that are hold in place by four wires attached on two sides of the tower. In figure 5(a) the tower is not stable when the wires are not attached on either of the two sides. In this situation, the only components holding the tower together are the connection joints mounted onto the rods with screws. When the wires are attached, the tower becomes stable, as seen in figure 5(b). In this configuration the tower is able to sustain a load on top of the tower of maximum 7.7kg. The tower by itself weights 262g, which is equivalent of the tower carrying a weight, 20cm over the ground, of roughly 29 times its own weight. Drop tests have shown that the tower could sustain a drop from up to 60cm and still withstand a top load of 7.7kg. With loads higher than 7.7kg or a drop from more than 60cm a random rotary joint would simply break. The broken joint could then be replaced and the tower would regain its strength. This test shows that LocoKit is able to be configured into a stable structure, with the ability to withstand great loads without using any power. It also shows that LocoKit has some of the same capabilities as construction kits like Erector and Meccano.

V. CONCLUSION

This paper introduces a new category of modular robotic systems, which we call “layered heterogeneous modular robots”. The system is divided into layers of heterogeneous modules, namely “Actuation”, “Electronics” and “Structure”, in order to lower the amount of overhead of electronics, motors etc. that normally is seen in modular robots. The purpose of this novel layered system is to create dynamic modular robots with increased locomotive capabilities. Tests have shown that the system at this early state is able to produce walking locomotion with speeds up to 11.8cm/sec and a specific resistance of 9.65. These tests also show that the dynamics of the system contributes to the locomotive performance and makes the performance of the robot comparable to that of other non-modular robots. Stable static structures build with LocoKit have also been tested. These tests show that the system is able to form lightweight structures that are able to carry up to 29 times their own weight 20 cm over the ground. These experiments support our hypothesis that layered heterogeneity increases the versatility of modular robots.

1) Acknowledgments.: The research leading to these results has received funding from the European Community’s Seventh Framework Programme FP7/2007-2013 - Future Emerging Technologies, Embodied Intelligence, under grant agreement no. 231688.

REFERENCES

[8] Jimmy Sastra, Sachin Chittay, Mark Yim: Dynamic Rolling for a Modular Loop Robot - GRASP Lab, University of Pennsylvania, Philadelphia, PA, USA
[17] Shadow Robot Company: Design of a Dextrous Hand for advanced CLAWAR applications - 251 Liverpool Road London ENGLAND