Hierarchical Robots

K. Stoy, A. Lyder, R.F.M. Garcia, and D. Christensen

***Abstract*— This paper introduces the concept of hierarchical robots, which is a type of modular robots assembled from a hierarchy of modules, and a preliminary realization of this concept: the Odin robot. Odin currently consists of ten modules of two different classes, one class of modules provide structure and the other actuation. We describe the mechanical design of these modules and their electrical design with specific focus on their hybrid communication system whose topology can be changed on-line. We demonstrate the features of this communication system in a simple experiment and also demonstrate how the assembled Odin robot can produce locomotion. While it is too early to make a conclusion regarding the usefulness of hierarchical robots in general, we think that our work indicates that we may be able to simplify the manufactured modules at the bottom of the hierarchy while increasing the functionality of the assembled hierarchical robot.**

I. INTRODUCTION

An animal is built from hierarchies of increasingly functional, modular systems. At the lower levels of the hierarchy, atoms combine to form molecules, at the middle levels molecules combine to form cells that combine to form organs and tissues, and at the highest levels organs and tissues combine to form the animal. This hierarchy allows nature to evolve animals to fit in biological niches relatively fast and with a high level of reuse. The biological world would certainly be a completely different place if all new species had to be evolved from scratch using the basic atomic and molecular building blocks.

The goal of this work is to transfer this concept of hierarchies to robotics and specifically to modular robots. In modular robots we connect modules to create a functional robot. In hierarchical robots we also connect modules to form a functional robot, but in addition the modules themselves are assembled from modules. These modules are again assembled from modules and so on until the lowest level of manufactured modules is reached. We refer to the lowest level of modules as the basic modules. The basic modules are heterogeneous and provide basic functionalities such as power, actuation, sensing and structure. The basic modules are connected using a common mechanical and electrical interface and thus provide an assembled higher-level module with more functionality than the individual, basic module provides. These high-level modules can then be combined to reach an even higher level of functionality and so on, until a hierarchical robot with the desired functionality is obtained. The hypothesis is that while reducing the functionality of the basic modules we may, through the use of hierarchies, still be able to increase the functionality of the assembled hierarchical robot.

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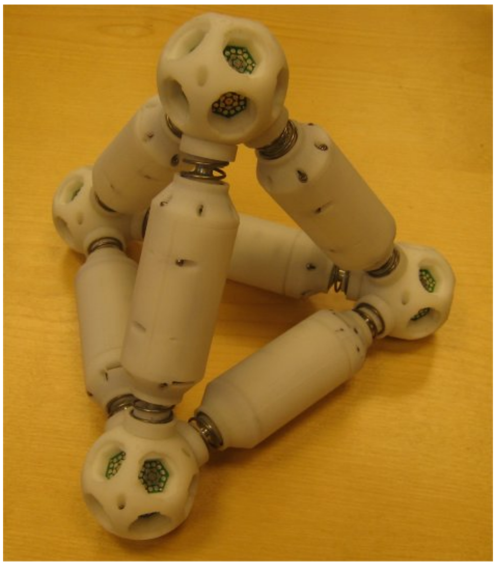


Fig. 1. The latest prototype of the Odin hierarchically modular robot. Six links connect four joints in a tetrahedron. Three of the links are actuated and can expand contract. This in combination with the flexibility of the connectors allow us to implement a tetrahedron locomotion gait, which we will describe in the experimentation section.

The hierarchical concept opens a discussion about at which level specific functionalities should be reached. E.g. the functionality of self-reconfiguration is traditionally tied to the level of individual modules. This, however, may not necessarily be the best level at which to implement it. As an alternative we may connect basic modules to form higher-level modules consisting of chains of basic modules, similar to meta-modules in self-reconfigurable robots [8], [5]. These chains of modules may in theory fold and become entangled rather than directly connecting to each other at the level of the basic modules. Whether this is practical or not is of course and open question and is one of the topics we will investigate in the longer term, but the point is that the hierarchical concept opens a discussion about which level to implement specific functionalities and thereby opens new approaches to traditional problems, in this case the problem of self-reconfiguration.

The hierarchical approach has several advantages. A hierarchical modular robot is extendible in the sense that we can develop new basic modules or even integrated, high-level modules if it is desirable. This gives us the possibility to incrementally build and extend our hierarchical robot, which also speeds up the development process significantly (the current prototype represents about eight man-month worth of work). Hierarchical robots also share some of the advantages of modular robots such as robustness, versatility, and cheapness: a modular design may allow a robot a bigger chance of surviving module failures, modules may be combined in a range of ways to produce a range of different robots, and the relatively limited set of basic modules can be mass-produced and thereby make them cheap compared to their complexity. Hierarchical robots may also exploit the functionality of basic modules to a higher degree than it is possible in homogeneous robots, because in homogeneous robots the full functionality of all modules is rarely used. This may lead to a reduction in the overall cost of the assembled robot even though more modules are needed.

In this paper we present a preliminary prototype of a hierarchical robot named Odin. We describe the mechanical and electrical design of Odin and underline the simplicity of its design. We also describe a hybrid communication system we have developed for this robot, which is particularly suited to hierarchical robots. In basic experiments we demonstrate the features of this communication system and we also demonstrate that a ten-module Odin robot is able to produce locomotion patterns not unlike those performed by conventional modular robots. While it is too early to conclude anything in general about the hierarchical approach, because we are not able to build multi-level hierarchies with only ten modules, we think that the simplicity of the module design combined with the functionality of the assembled robot so far support our hypothesis or at least indicate that there may be an unexplored potential in hierarchical robots.

II. Related Work

The concept of hierarchical robots is inspired by work done in a number of research fields. The most obvious is the field of self-reconfigurable robots, examples of which can be found in [10], [14], [9], [2], [11]. Self-reconfigurable robots are also modular, but in addition they are able to autonomously change the way modules are connected and are thereby able to change shape by themselves. Hierarchical robots are not self-reconfigurable, but as mentioned might provide an alternative path to realizing self-reconfiguration at a higher level than the individual modules by having chains of basic module tangle. Another problem in self-reconfigurable robots is how we provide the robot with capabilities greater then the capabilities of the individual modules. E.g. collective actuation is the question of how we make modules work together to provide a large enough force to exert forces on the environment greater than what can achieved by a single module [1]. Hierarchical robots also provide an interesting context in which to study this question and in general how we may provide functionality beyond that provided by individual modules. We have used the concept of hierarchies before in the context of self-reconfigurable robots [4], but the scope of the current work is different, because we insist on simple and heterogeneous basic modules as opposed to more complex ones as the starting point for the hierarchy. Heterogeneous modules have also been proposed before in the context of self-reconfigurable robots [6], but in addition to the hierarchy we use heterogeneity to create simpler modules rather than to add functionality to individual modules in an otherwise homogeneous modular robot.

The hierarchical approach is also inspired by work on self-replicating robots. In work by Chirikjian et al. [3] it is shown how a number of simpler pieces can be assembled by a constructor robot to form another constructor robot. From the point of view of hierarchical robots this system is a two-level hierarchy. A two-level hierarchy is also used by Zykov et al. [15], but rather than using a constructor robot they use a self-reconfigurable robot and as such the complexity of their basic modules is high. In our work the aim is to make multi-level hierarchies by extending the hierarchy both down to make smaller, simpler modules and up to build more functional robots. In addition our goal is not self-replication, but hierarchical robots might provide a potential way to realize self-replication if the basic modules can be simplified to a degree where they can be constructed from materials available in the environment and assembled by multi-level hierarchical robots.

Finally, we are inspired by deformable modular robots [12]. Deformable modular robots are robots who derive some of their functionality from the mechanical properties of the modules from which they are built. E.g. rigid modules provide structural strength, flexible modules allow modules to deform in response to external or internal forces.

In summary, we see hierarchical robots as unique because they derive their functionality from a multi-level hierarchy of modules, their basic modules are simple and heterogeneous, and basic modules have limited functionality individually.

III. The Odin Robot

Our first attempt at realizing a hierarchical robot is the Odin robot that we will describe in this section.

A. Mechanical Design

The robot is built from two kinds of modules: *links* and *joints*. The links are cylinders with a diameter of 35mm and a length of 110mm. A link has a male connector at each end. This mechanical design is shared by all types of link modules. We are planing to build links belonging to four different classes: structure, actuation, power, and sensing. However, currently only two classes of modules have been realized: structure and actuation. The structure modules we have developed are equipped with RGB LEDS that allow us to control their color and the actuator modules are equipped with a stepper motor that allows them to expand to a length of 150mm. The joint modules are spheres with a diameter of 50mm. Distributed evenly around each sphere are twelve female connectors. This design allows joints to be fully connected by links to form a cubic closed packed lattice. An Odin robot consisting of four joints and six links can be seen in Figure 1.

The connector is a lock-and-key mechanism where the male part is inserted into the female and rotated to lock.

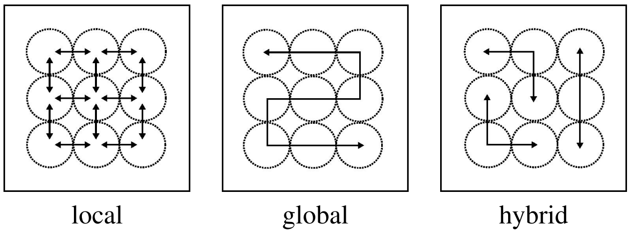


Fig. 2. This figure explains the flexibility of the Odin communication systems. Using the same fundamental hardware local busses, a global bus or hybrid busses can be dynamically created at run-time.

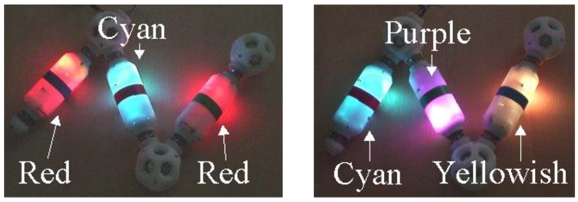


Fig. 3. This figure shows three Odin modules connected through two joints. Initially, modules are connected by a local bus. The modules are programmed to assume a combination of the color commands received. E.g. in the left figure the middle module sends out "red" and thus both neighbor modules turn red. The right module sends out "green" and the left "blue" and therefore the middle module turns turquoise. In the right figure the buses of the joints are electrically connected and the modules starting from left transmit "red", "green" and "blue" and turn into a mixture of the colors transmitted by the other two modules demonstrating that they are now on the same bus and are able to communicate.

On the link side of the connector is a spring-loaded ball-and-socket joint that provides the connector with flexibility. The spring returns the connector to a straight position if the external forces are not too strong. Through the connector run four wires that provide communication and power. The details of this will be described in the following section.

B. Electrical Design

Four electrical connections are made between the connectors of the link and the joint modules using spring contacts. The four electrical connections provide two wires for power and two for communication. The pads in the female connector are replicated six times at 60° intervals, which allow the links to be connected at six different orientations with respect to the joint.

Electrically, a joint connects all the pads of all its connectors of the same type. E.g. all the *ground* pads of a joint are electrically connected. The links are more sophisticated. A general printed circuit board provides the link with computation power using an ATMEL ARM7 processor with 256Kb flash and 64Kb SRAM and the means to communicate electrically with neighbor links through the joints. Currently, the robot is powered externally and a power bus is distributing the power throughout the entire system, but a battery modules is under development that will allow us to run the robot autonomously. All links provide the basic functionalities of computation, communication, and power-sharing. In addition, each link has a specific electronics board that provides the specific functionality of the corresponding class of links. Currently, we have three LED links and three linear actuator modules with corresponding specific electronics boards. Both the general and the specific boards are circular with a radius of 25mm to allow it to fit inside the frame of the links.

The communication system is quite unique. Rather than having a purely local communication system or a global communication system we have implemented a hybrid communication system [7]. In this system all modules connected to the same joint are on the same physical bus and can, therefore, communicate directly with each other. Inside each link there is a software-controllable switch that allows the busses of two joints to be connected to form one bus. This means that we from software can control how the communication network inside the robot is organized. We can have purely local communication or purely global communication and everything in between as shown in Figure 2. The physical layer is a RS485 bus. Great care has to be taken when choosing termination impedance to insure stable communication at high speeds [7]. Theoretically, the bus can achieve communication speeds of up to 620Kbps with a maximum of 256 modules connected. We refer to the bus system as a hybrid bus. We believe that such a bus system is useful in modular robots because it provides robots consisting of a large number of modules with a communication system that is both scalable and fast. Of course this bus system also ties in nicely with our concept of hierarchies because the underlying communication system can also be organized hierarchically.

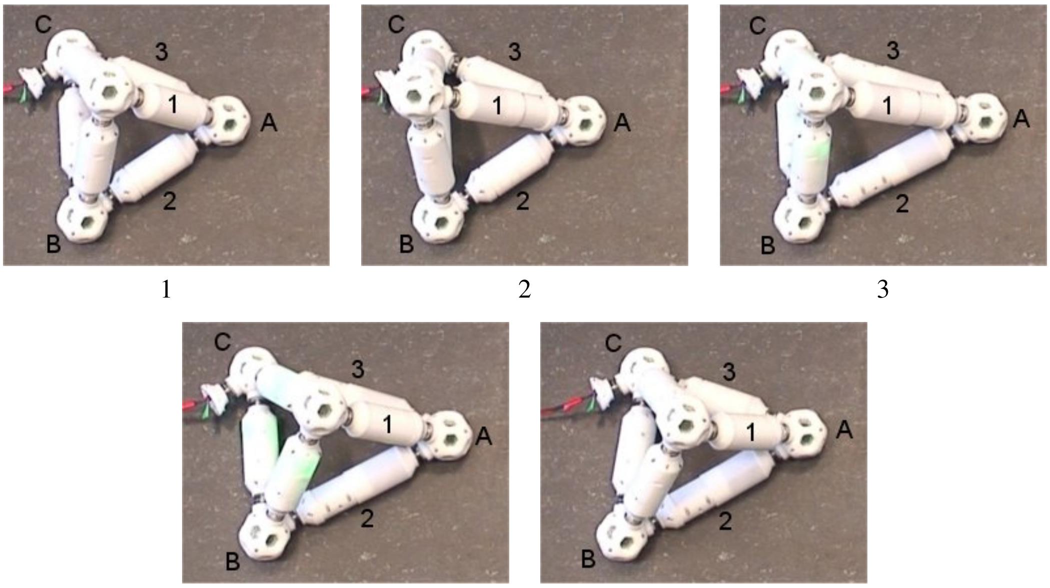
The Odin modules are currently powered externally and the power is distributed across the entire system through the various connectors. This design is only preliminary and we are currently working on a power control board for the modules and electronics for a battery module. The goal is to have a number of isolated power circuits within an Odin robot and preferably power modules will be placed close to power-hungry modules such as actuators to prevent large currents. The power routing system is currently work in progress, but we may essentially implement a hierarchical power system similar to the communication system.

IV. Experiments

In this section we will present some simple experiments that demonstrate the capabilities of the Odin robot.

In the first experiment we demonstrate the hybrid communication. The experiment, outlined in Figure 3, demonstrates that we are able to make local busses on each joint as well as global busses connecting all joints. Note, that the transition between local and global communication is performed on-line.

In the second experiment we demonstrate the basic functionality of the system. We connect six links and four joints to form a tetrahedron. The three active actuator links are controlled using an adapted version of role-based control [13], which is a distributed control method. The tetrahedron is able to move forward as described in Figure 4 and achieves a modest speed of 0.5 cm/second.



1 2 3

4 5

Fig. 4. This figure shows one cycle of tetrahedron walking towards the right. 1) modules labeled with numbers are actuator links. 2) first actuator link 1 expands to transfer weight to the rear two points of ground contact and thus increase their friction. 3) then actuator links 2 and 3 expand to move ground contact point A forward. 4) actuator link 1 is contracted to increase the friction of A. 5) actuator link 3 is contracted and after that actuator link 2 (shown in 1) and then the cycle repeats.

Currently, we only have six links, three LED links and three actuator links, and four joints, which makes it difficult to do more complex tasks than the one described here. The experiments, however, demonstrate that already at this early stage we can build a robot from simple, heterogeneous basic modules that can perform a simple locomotion gait. Future work involves creating more links and also new types that will allow us to pursue more complex tasks while from a scientific point of view explore the potential of hierarchical robots.

V. Conclusion

In this paper we presented the concept of hierarchical robots. Hierarchical robots are characterized by consisting of a hierarchy of modules. Simple, heterogeneous modules combine to form functional modules, which again combine to form either more high-level modules or a functional robot. We presented the mechanical and electrical design of the hierarchical robot Odin with focus on the hybrid communication system whose functionality is demonstrated in a simple experiment. We also demonstrated that at this early stage of our development we are able to build a tetrahedron consisting of ten basic modules that are able to produce locomotion. Even though the development of the Odin robot is work in progress the obtained results encourage us to continue to pursue the hierarchical approach to robotics.

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