Research article

Exploring adaptive locomotion with YaMoR, a novel autonomous modular robot with Bluetooth interface

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Abstract
Purpose – This paper aims to present a novel modular robot that provides a flexible framework for exploring adaptive locomotion.
Design/methodology/approach – A new modular robot is presented called YaMoR (for "Yet another Modular Robot"). Each YaMoR module contains an FPGA and a microcontroller supporting a wide range of control strategies and high computational power. The Bluetooth interface included in each YaMoR module allows wireless communication between the modules and controlling the robot from a PC. A control software called Bluemove was developed and implemented that allows easy testing of the capabilities for locomotion of a large variety of robot configurations.
Findings – With the help of the control software called Bluemove, different configurations of the YaMoR modules were tested like a wheel, caterpillar or configurations with limbs and their capabilities for locomotion.
Originality/value – This paper demonstrates that modular robots can act as a powerful framework for exploring locomotion of a large variety of different types of robots. Although present research is limited to exploring locomotion, YaMoR modules are designed to be general purpose and support a variety of applications.

Keywords Robotics, Control systems, Configuration management

Paper type Research paper

Introduction

Modular robots offer a robust and flexible framework for exploring adaptive locomotion control. By reusing basic building blocks modular robots present many advantages over conventional monolithic robots:

- Modular robots support a fast reconfiguration of their structure. They allow assembling robots of different types, e.g. snakelike robots, robots with limbs, and many other different shapes. To build a robot of the desired form it is not necessary to construct a completely new robot but it can be assembled by simply disconnecting and reconnecting modules.
- By reusing modules the development time for new robot configurations can be reduced dramatically decreasing time to market.
- The reconfiguration of their structure allows adapting a modular robot to a particular task. This adaptation becomes especially powerful, when the robot supports self-reconfiguration like shown for the M-TRAN (Kurokawa *et al.*, 2003).
- Modular robots potentially offer a better reliability and robustness than conventional monolithic robots because damaged modules can be ejected and replaced by redundant modules.

Locomotion with modular robots constitutes a great potential but at the same time a very difficult challenge because control strategies have to be found that allow benefiting from the modularity and flexibility of the hardware. In particular, the challenge is to design distributed locomotion controllers that can adapt to body structures that are unknown in advance, and that might change over time due to structure reconfiguration.

Numerous modular robots can be found in the literature. Lattice robots like MAAM (Gueganno and Duhaut, 2004), Crystalline (Vona and Rus, 2000), Telecube (Vassilvitskii *et al.*, 2002), Fractum (Tomita *et al.*, 1999), ATRON (Østergaard and Lund, 2003) and I-Cubes (Unsal *et al.*, 2000) locomote by moving modules to neighbouring positions on a lattice. Chain robots like M-TRAN (Kurokawa *et al.*, 2003), Polybot (Yim *et al.*, 2002), Conro (Castano *et al.*, 2002) and Y1 (Gonzalez-Gomez and Boemo, 2005) form various types of robot configurations from chains of modules. ORTHO-BOT (Ramchurn *et al.*, 2005) is a concept for modular

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Emerald
Industrial Robot: An International Journal
33/4 (2006) 285–290

[ISSN 0143-991X]
[DOI 10.1108/01439910610667908]

This is an updated and edited version of the paper first presented at CLAWAR 2005, London, UK 13-15 September 2005.
The authors would like to acknowledge André Badertscher for the technical support, Alessandro Crespi, Fabien Vannel and René Beuchat for many useful discussions and hardware debugging. This work was partially supported by the Swiss National Science Foundation through a Young Professorship Award granted to Auke Ijspeert.

Industrial Robot: An International Journal
Volume 33 · Number 4 · 2006 · 285–290

reconfigurable space robot. Swarmbots (Mondada *et al.*, 2002) are autonomously moving robots that interact with each other to form more complex structures.

Our modular robot – YaMoR – is a chain robot that is designed to act as a cheap platform for:

- testing different control algorithms for locomotion and their implementation in both software and hardware;
- exploring the capabilities for locomotion of a large variety of different robot configurations and shapes; and
- finding new applications for wireless networks.

The main characteristics of our modular robots are:

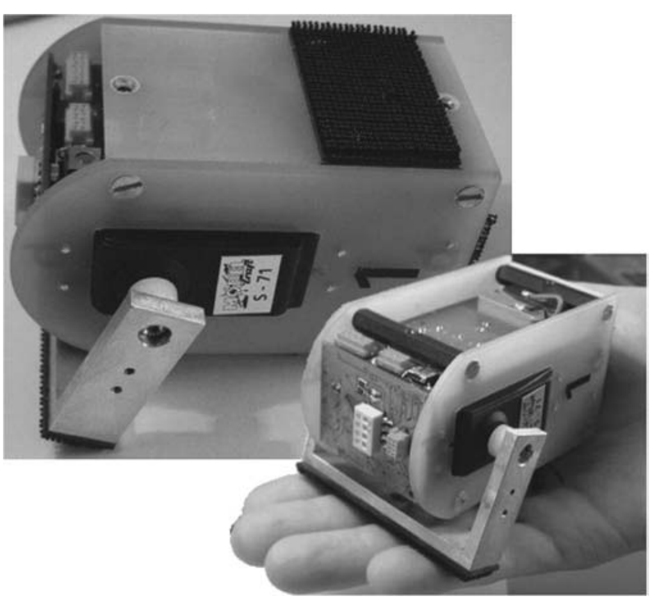
- Each module contains a Bluetooth interface for wireless inter-module communication as well as for communication between the modules and a base station like a PC – most modular robots use direct electrical connections, which are less flexible.
- Each module comprises an FPGA for reconfigurable computation – most modular robots use traditional microcontrollers, but see (González-Gómez *et al.*, 2004) for an example of a robot using a single FPGA for controlling all modules and (Gueganno and Duhaut, 2004) for a modular robot using an FPGA for each module.

We designed and implemented a control software called Bluemove that allows to control the YaMoR modules from a PC via Bluetooth. Together YaMoR and Bluemove act as a framework for exploring the capabilities for locomotion of different configurations of modules. The framework is very easy to use: by connecting modules by hand new robot configurations can be assembled. The robot can easily be controlled by setting key points on a graphical user interface (GUI) with a mouse. This paper is an extended version of an article presented at CLAWAR 2005 (Moeckel *et al.*, 2005).

YaMor – mechanics and electronics

YaMoR consists of mechanically homogeneous modules. One of the key features of YaMoR is its low cost: in contrast to the majority of modular robots, YaMoR is constructed with off-the-shelf components. Each module contains a powerful one degree of freedom servo motor (with a 73 Ncm maximal torque). Its casing consists of cheap printed circuit boards (PCB) that can also serve as support for printed circuits (Figure 1).

Figure 1



The casing of each module is covered with strong velcros. Velcros offer the advantage to connect robot modules together with no restriction on angles between the surfaces of the modules. Unfortunately, it does not support self-reconfiguration and the modules can only be connected together by hand.

The modules are autonomous. They are powered by on-board Li-Ion batteries and include the necessary electronics for power management, motor control, communication and execution of algorithms. To achieve more flexibility and modularity in terms of control each YaMoR module contains three separated control boards:

1. one board including a Bluetooth-ARM microcontroller combination;
2. one board carrying a Spartan-3 FPGA; and
3. a service board containing power supply and battery management.

YaMoR was constructed as a framework for a variety of different projects. For instance, a user may choose between using an ARM7TDMI microcontroller – used in a variety of industrial and research projects – an FPGA or a combination of both for implementing the desired control algorithm. Configuring the FPGA to contain a MicroBlaze soft-processor[1], allows exploiting the hardware-software co-design capabilities offered by the platform, taking also advantage of the flexibility provided by the FPGAs partial reconfiguration feature (Upegui *et al.*, 2005).

The YaMoR architecture with distributed electronic components gives a flexible solution for connecting the electronic boards: the FPGA board can be left out if it is not needed to save energy; or it can be replaced by a board with specific sensors if useful. The new sensor board can still take advantage of the electronics mounted on the remaining boards. So a designer for an additional sensor board does not have to worry about power supply or battery management.

Bluetooth – the wireless interface to YaMor

We chose Bluetooth for wireless communication given its flexibility and energy efficiency. Bluetooth is a popular standard developed by the Bluetooth Interest Group[2]. Using the Bluetooth standard as wireless interface provides the following advantages:

- it allows us to benefit from later developments and improvements of this technology;
- to communicate with other Bluetooth devices like Bluetooth dongles or Bluetooth interfaces that can be found in PCs, mobile phones and PDAs;
- given the popularity of Bluetooth it is possible to buy Bluetooth chips for low price; and
- furthermore, Bluetooth is working in the 2.4 GHz license-free frequency band.

This has the advantage that no fees have to be paid for sending data via Bluetooth. On the other hand, a large variety of standards are sharing the 2.4 GHz frequency band. However, taking benefit from frequency hopping, Bluetooth has proved to be a very robust standard that can easily operate while other standards like WLAN are working in the same band.

Wireless communication between modules allows us to create a new robot configuration by simply disconnecting and reconnecting the mechanical modules without the need for reconnecting cables or changing the control infrastructure. Furthermore, it supports to control a robot from a base station – like a PC – without disturbing wires. In comparison to a communication based on wires, Bluetooth has the constraint that a module normally does not know its physically connected neighbours just by communicating with them. However, this constraint can be overcome with the addition of other communication modalities, e.g. using LEDs and light receptors (currently under investigation).

The ARM on the Bluetooth board is running both a real time operating system and the embedded Bluetooth stack. It can also be used for customized software, e.g. a control algorithm or for reconfiguring the FPGA via Bluetooth. The ARM program code and FPGA configuration bitstream are stored inside a flash memory on the microcontroller board.

The Bluetooth-ARM board was designed to provide a wireless interface that can be easily controlled. The embedded Bluetooth stack allows taking advantage of wireless communication by sending simple commands via UART to the ARM. For instance, a researcher concentrating on FPGA based algorithms may implement a simple UART module on the FPGA and is able to communicate wirelessly with a PC or other modules.

Bluemove – controlling YaMor via Bluetooth

For easily exploring new configurations of modules and their capabilities for locomotion, an interactive Java based control software called Bluemove has been developed. Using a GUI on a PC, a user can quickly start a new project, register all modules used for the current robot configuration and implement a controller. To control the modules Bluemove allows three different methods:

1 writing trajectories that can be continuously sent to the modules via Bluetooth and interactively modified without any resetting;
2 the use of plugins for controlling the modules from a PC; and
3 programming the FPGAs as well as the ARMs for autonomous control in the modules without needing a PC.

Plugins can act as inputs (hand-drawn trajectories, generators, oscillators, etc.), filters (signal processors, multiplexers, etc.) and outputs (data sent to the modules, files, streams, etc.). Plugins support the generation of controllers with feedback from sensors. The whole project including the trajectories and plugins can be saved in XML. The main parts of the GUI are:

- The module manager serves to manage all modules belonging to the current robot configuration including module names and Bluetooth addresses of the modules.
- The timelines manager allows generating trajectories for each actuator of the modules registered in the module manager by setting key points on the GUI with a mouse. Linear and spline interpolation can be chosen to draw the trajectories and connect the key points set before. Trajectories can even be changed "online" while transmitted to the modules, e.g. by changing the position of the key points.
- The real-time module supports an easy use of Bluemove with the help of plugins. New plugins can be created with a script editor. The relations between different plugins are visualised with the help of a graphical display.

Bluemove is implemented in Java, taking advantage of its standard and consistent interface for Bluetooth. Given the popularity of Bluetooth and Java, it would be possible to create Bluetooth applications for the modular robot on mobile phones, PDAs or other small systems that support Java and Bluetooth (Figures 2 and 3).

Exploring locomotion

We explored the locomotion capabilities of different YaMoR configurations with up to six modules, using Bluemove to generate the joint angle trajectories for the servo motors. By trial and error, interesting gaits could be generated for a variety of robot structures, such as travelling waves for worm and "wheel" structures (for four snapshots of a rolling wheel), crawling gaits for limbed structures, and other peculiar modes of locomotion (for different examples of configurations of YaMoR modules). For videos, the reader is kindly requested to visit the project web site (YaMoR project web site, URL http://birg2.epfl.ch/yamor).

These gaits are only a first step towards adaptive locomotion (see next section), but already represent in our opinion an interesting example of control with a "human in the loop". The user can indeed interactively adjust the gaits in real time, in order to optimize the speed of locomotion for instance, as well as modulate the gaits in terms of speed and direction, by modifying frequency and amplitude parameters.

For exploring more complex shapes of a robot, tests with more than six modules are needed. For example, most of the configurations tested so far do not allow changing the direction of the movement, and would therefore, not be capable of avoiding or overcoming obstacles (Figures 4 and 5).

Current and future work

To achieve adaptive locomotion, the "human in the loop" control that we were using for the first experiments is clearly not sufficient. In a complex environment a robot has to react autonomously and adapt in real time. That is why we designed Bluemove to also support feedback signals from sensors with the help of plugins. Distributed algorithms can be implemented in the ARM and FPGA of each YaMoR module. Both the parameters of these algorithms and the shape of the modular robot can be optimized under different constraints like energy efficiency or speed.

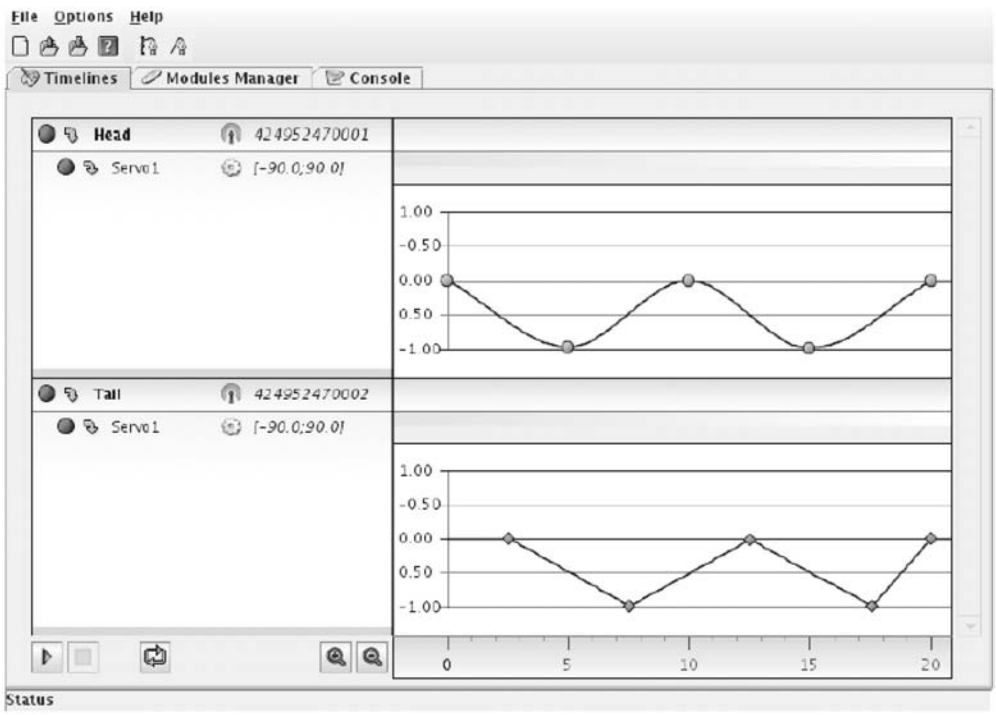
We are currently extending the presented work along two main axes:

1 the design of the next generation of YaMoR modules with sensors capabilities, e.g. IR sensors, inertial sensors, and load sensors; and
2 the implementation of distributed locomotion controllers based on central pattern generators (CPGs).

CPGs are biological neural networks capable of producing coordinated patterns of rhythmic activity while being initiated and modulated by simple input signals (Ijspeert *et al.*, 2005). For the control of robots, CPG models can be implemented as systems of coupled nonlinear oscillators or as recurrent

Industrial Robot: An International Journal
Volume 33 · Number 4 · 2006 · 285–290

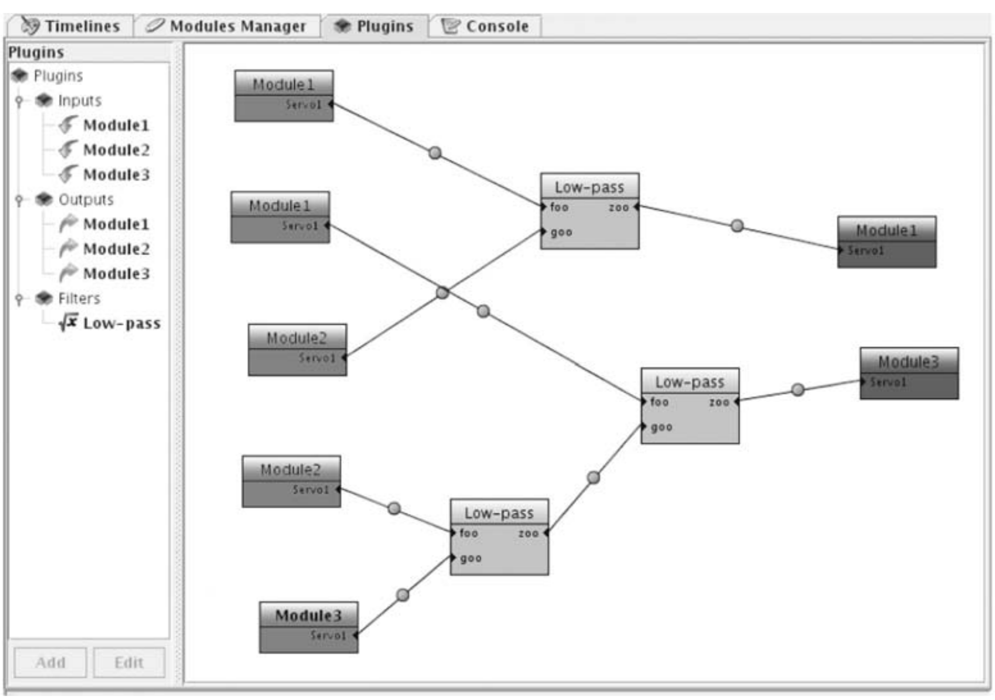
Figure 2



neural networks. CPGs are particularly interesting for robotics for three main reasons:

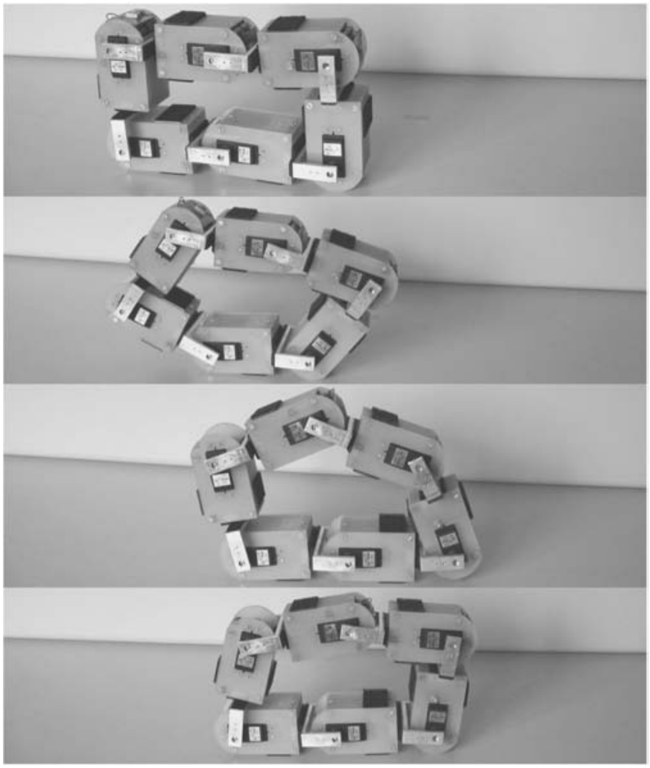
1. they encode gaits as limit cycle behaviours (from a dynamical systems' point of view) and this offers strong robustness against perturbations (i.e. perturbations are quickly damped out);
2. they can initiate and modulate gaits by the variation of a few simple control signals, and they therefore, drastically reduce the dimensionality of the locomotion control problem; and
3. they support smooth transition between different gaits.

Figure 3



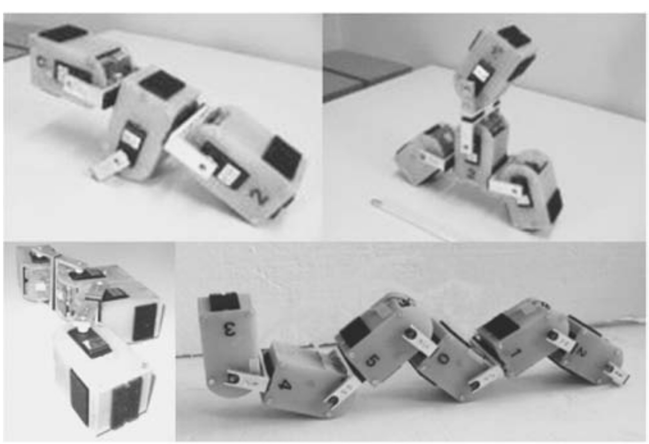
Industrial Robot: An International Journal
Volume 33 · Number 4 · 2006 · 285–290

Figure 4



This is especially interesting since motors can be damaged when the desired motor positions are frequently changed too abruptly. CPG-based control has recently been used by Kamimura *et al.* (2004), who use two-neuron Matsuoka oscillators as a CPG model for M-TRAN. We have extensively used models of CPGs for the control of locomotion in other projects like for snake and salamander-like robots (Ijspeert, 2001; Crespi *et al.*, 2005). Furthermore, we tested CPGs with simulated robot configurations of YaMoR modules with the help of the open dynamics engine[3]. While Bourquin (2004) evolved the free parameter of the CPGs for fixed robot configurations, Marbach also co-evolved the configuration of the modular robot (Marbach and Ijspeert, 2005). One approach combining CPG models and Powell's optimization method has led to online optimization of efficient gaits in remarkably little time, usually less than half an hour of operation time (Marbach and Ijspeert, 2005). Such an approach outperforms other optimization methods reported in the literature, and will soon be tested for online optimization with the real YaMoR units.

Figure 5



Conclusion

We presented a new framework for exploring adaptive locomotion. The framework contains YaMoR – a new modular robot – and Bluemove – our software for controlling YaMoR online via a Bluetooth interface. By using a modular robot we can explore the capabilities for locomotion of a large variety of robot configurations without redesigning mechanics and electronics for each particular type of robot. New robot configurations are obtained by simply disconnecting and reconnecting the YaMoR modules. This leads to a dramatic reduction of development cost and offers new opportunities in terms of flexibility and robustness. Because we support a wireless Bluetooth interface, robot reconfigurations can be realized without the need of disconnecting and reconnecting wires and without changing the control architecture. YaMoR was designed to be cheap and to be general purpose. Containing both an FPGA and a microcontroller, YaMoR modules have the computational power to support a large variety of applications.

Notes

1 Xilinx Corp., MicroBlaze™ URL www.xilinx.com
2 Bluetooth Interest Group, URL www.bluetooth.org/
3 Russell Smith. Open Dynamics Engine (ODE), URL http://ode.org/

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