New Autonomous, Four-Legged and Humanoid Robots for Research and Education

Martin Friedmann[1], Sebastian Petters[1], Max Risler[1], Hajime Sakamoto[2], Dirk Thomas[1], and Oskar von Stryk[1]

[1] Technische Universität Darmstadt, Department of Computer Science
Hochschulstr. 10, D-64289 Darmstadt, Germany
{friedmann|petters|risler|dthomas|stryk}@sim.tu-darmstadt.de,
WWW home page: http://www.sim.tu-darmstadt.de

[2] Hajime Research Institute, Ltd., 19 Miki-Seisakusyo 1-7-28 Ohno,
Nishiyodogawa-Ku, Osaka 555-0043, Japan, sakamoto@hajimerobot.co.jp,
WWW home page: http://www.hajimerobot.co.jp/

Abstract. Prototype models of new, fully programmable, autonomous four-legged and humanoid robots are presented as powerful standard platforms for research and education. They are based on an open and modular concept for hardware and software and exhibit a multitude of interfaces, sensors and powerful motion capabilities.

1 Introduction

Bio-inspired artificial intelligence (AI) needs a body. The type of body is determined by the degrees of freedom of independent sensing and motion capabilities as well as planning capabilities on onboard computers. The specific body shapes the type of AI which can be developed on such a robotic platform to perform interactions in a dynamically and changing environment for solving complex tasks autonomously. Or as R. Brooks et al. claimed "Humanoid intelligence requires humanoid interactions with the world" [1]. In many scenarios having a humanoid or at least a legged robot can be beneficial or even mandatory. Not only is legged locomotion an interesting and active research domain. Research on humanoid or other legged, animaloid robots can also be fruitful when investigating human-robot-interaction or whenever robots are supposed to operate in the same environment as humans.

Between 1999 and 2006 the four-legged Sony AIBO robot [2] has found remarkable acceptance. It was, however, not only used for its original determination as a home entertainment robot, but also found widespread use as an affordable, ready-to-program standard platform for many research and educational robotics projects at universities. This success was due to the multitude of sensing and motion abilities of the robot and to Sony's release of a programmable interface based on OPEN-R [3] which allowed to read the robot's sensors and to send commands to its actuators and to develop specific application software for autonomous robot operation. One of the many applications and presumable

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the most widespread one has been the use and investigation of the robot as a standard platform for cooperating autonomous robot soccer teams in the Four-Legged Robot League [4] of RoboCup [5] since 1999. As the production of AIBO has been discontinued in 2006 there is a need for new autonomous robot platforms for such research and educational purposes in robotics, embedded systems, or artificial intelligence.

New platforms for such autonomous, four-legged and humanoid robots for research and education must meet a number of requirements:

- Ready to program: All sensors and actuators of the robot should be fully programmable with standard programming languages. The effort for new developers to get their own software running on the robot should be minimal.
- High performance in motion, sensing, and computing power: Motion, sensing, and computing capabilities need to be state of the art in order to be competitive with comparable platforms.
- Open, modular and reconfigurable software *and* hardware: An open platform allows researchers to customize the platform according to their specific requirements. Complete access to hard- and software specifications is necessary in order to make full use of the capabilities of the platform, e.g., by reconfiguration of a sensing or motion ability.
- Many degrees of freedom: The robot should have a sufficient number of degrees of freedom in order to create interesting new behaviors and modes of locomotion.
- Full Autonomy: The robot is required to be fully autonomous. That is, it must have onboard computing resources sufficient to meet all processing requirements. Onboard battery power must ensure reasonable operation periods.

In the remaining of this paper we describe the design issues and selections undertaken to meet the above mentioned requirements in mechanics and kinematics, sensing, and computing abilities for the development of new four-legged and humanoid robot prototypes. The presented robots are fully programmable and suitable as autonomous standard platforms for research and education.

2 Design of the Robots

In the following section the mechanical design, computing and sensing capabilities of the two robots are discussed. One key idea during the design process was to have as much similarities in the two systems as possible to allow the transfer of know how from one robotic system to the other.

2.1 Kinematical and Mechanical Design of the Robots

Four legged robot For the four legged robot various kinematical designs were considered and tested in a 3D kinematic motion and camera simulation (see Figs. 1 and 2). Each leg consists of three rotational joints. Special attention

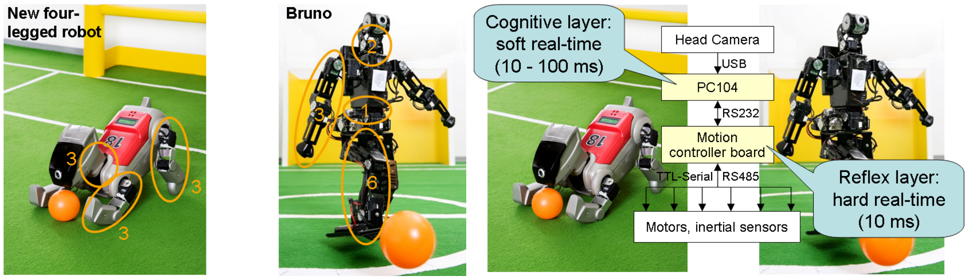


Fig. 1. Left: Degrees of freedom of the four-legged (15) and humanoid (21) robot; right: computational layers

was also given to the design of the robot's head and neck joints which features three degrees of freedom allowing to look in any direction including backwards (through the legs) as well as a wide range of motions for ball manipulation. The final kinematic design allows a wide range of motion capabilities which include the well established low stance walking on the forearms which was common in the RoboCup Four-Legged League on the now discontinued Aibo platform. This walking gait has the advantage that a lower height of the center of gravity above ground is more stable with respect to shocks. Also the robot can see a ball directly in front of it and can still see parts of the environment. This has not been possible for an upright gait with the AIBO. The new robot therefore is designed of being able to position the head for looking forward at high and also low height above the ground. Furthermore, the robot can look underneath its torso to the back and see the world behind upside down. It can now also kick the ball with the head underneath the torso to the back.

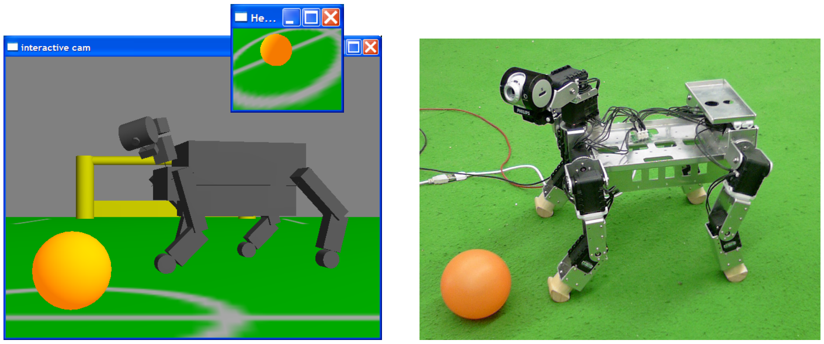


Fig. 2. Left: Simulation of the locomotion of the proposed four-legged robot and images captured from its simulated camera; right: model of its mechanical motion apparatus.

The four legged robot uses Robotis AX12+ servo motors providing a torque of 16.5$kgfcm$ at 10 V operation voltage and speed of 0.196/60 degs which is high enough to expect about the same speed of locomotion as could be achieved with a Sony AIBO in RoboCup. The servos use the same logical protocol and provide the same monitoring features as the stronger Robotis servos used in the humanoid robot. Instead of the RS485 bus a one-wire bus is used for communication. The servos are connected by a serial bus with the main controller, allowing high control rates (125 Hz and higher). The robot is powered by 3 cell LiPo batteries.

Humanoid Robot The mechanical design of the humanoid robot (cf. Fig. 1) has evolved over several generations of robots used in the RoboCup humanoid kid-size league. Initially the kinematical design featured 24 degrees of freedom (6 per leg, 4 per arm, 2 in the hip and 2 in the neck), which were realized by DX117 servos by Robotis. Analysis of a prototype showed the overall fitness of the robot for the desired task, namely participating in the RoboCup competition, but also revealed some deficits. A major problem are the high loads on servo motors placed in the robot's knees and hip. To reduce this load, the overall weight of the robot was reduced by removing one servo from each arm and the hip hereby reducing the number of actuated rotational joints to 21. Further on the remaining servo in the hip and the servos in the robot's knees were replaced by the stronger DX64 servos by Robotis. This basic mechanical design was used in RoboCup 2006 and (with minor changes) RoboCup 2007. In both competitions the robot was among the best performing robots. The final design presented in this paper was developed for the 2008 RoboCup competition. The only mayor change was replacing the DX117 servos by the newly developed RX28 servos.

All servos of the Robotis' DX and RX series feature the same physical bus (RS485) and the same communication protocol. The servos provide a wide range of monitoring capabilities including current position, velocity, temperature and load.

The robot is powered by 4cell LiPo batteries providing a nominal voltage of 14.4 V. Batteries with 1300 mAh capacity lasted at least 15 minutes during normal operation. A low-loss voltage converter is used to derive the 5V necessary to operate the onboard PC and microcontroller.

2.2 Sensing

External sensors. The main external sensor of both robots is a camera mounted to the head (Fig. 3). Standard off-the-shelf webcams using USB connections have been used for both robots.

The humanoid robot uses a Philips SPC1300 webcam. This camera provides a maximum resolution of 1.3 MP and a maximum frame rate of 90 fps. The horizontal aperture angle is 80 degrees.

In the current design the four-legged robot uses a Philips SPC900 webcam providing a resolution of 640x480, a frame rate of up to 90 fps and an horizontal aperture angle of 45 degrees. As this camera is no longer manufactured it will be replaced by the camera used in the humanoid robot.

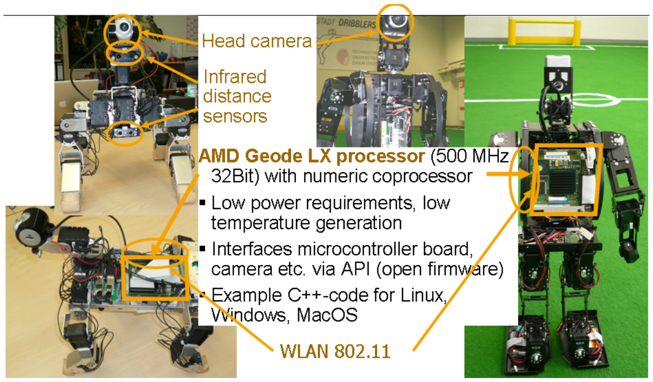


Fig. 3. External sensors and main onboard computer of the four-legged and humanoid robot.

Both cameras have exhibited a very good performance, e.g., in distinguishing different colors at different lighting conditions. Drivers for both cameras are available for current windows platforms as well as for Linux.

The four-legged robot provides auxiliary sensing capabilities by two infrared distance sensors located in the chest and the head. These sensors allow detection of objects independent of the motion of the robot's body and provide a measuring range of 10 to 80 cm.

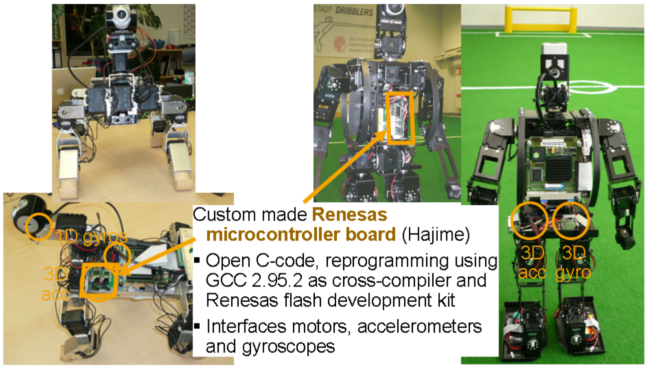
Internal sensors. Both robots provide inertial sensing capabilities (Fig. 4). A 3DOF acceleration sensor which can be used to detect the robot's pose (e.g. detection, if the robot has fallen over) is mounted to the torso of each robot. The humanoid robot features three gyroscopes mounted to its hip allowing postural stabilization of biped motions and inertial navigation. Only two gyroscopes have been used for the four legged robot. One gyroscope is mounted to the torso allowing measurement of the robot's angular velocity around the vertical axis allowing improvement of the robot's odometry. The second gyroscope is mounted to the robot's head to enable research in the field of inertial stabilization of the camera's field of view during walking.

The servos used in both designs provide extended sensing capabilities including current position, velocity, temperature, load and supply voltage. All measurements can be accessed by the respective bus of the servos.

2.3 Computing Capabilities

Both robots are equipped with an onboard PC and an additional microcontroller circuit for interfacing with the servos and sensors (Fig. 3).

Onboard PC. Both robots use a PC104 embedded PC board. A wide range of different CPU boards are available for this standard, thus allowing easy upgrade



Custom made **Renesas microcontroller board** (Hajime)

- Open C-code, reprogramming using GCC 2.95.2 as cross-compiler and Renesas flash development kit
- Interfaces motors, accelerometers and gyroscopes

Fig. 4. Internal sensors and custom made microcontroller boards of the four-legged and humanoid robot.

of the robot. It is also possible to add specialized expansion cards to the PC104 connector of the PC board.

For the presented robot a CPU board with 500 MHz Geode CPU was chosen. This boards features a wide range of standard interfaces, including USB2.0, VGA, audio and 100 MBit Lan. Up to 1024MB of RAM may be installed. For wireless comunication an USB WLAN adapter is included. The onboard PC uses a compact flash card as hard-disk replacement. Several operating systems, including Windows CE and Linux are supported.

On the backside of the four legged robot is an opening providing easy access to a number of I/O interfaces and to the LiPo batteries: a 1 GBit LAN Ethernet slot, a compact flash card slot, a plug-in for a monitor cable, and 2 free USB ports. The latter can be used very flexibly, e.g., to plug keyboard and mouse directly to the onboard computer or to add additional devices like a microphone, a loudspeaker or an extra camera. On the robot's back a display (with two lines of 16 characters each) is provided enabling some online monitoring and debugging as well as 4 push buttons for programmable commands like start or stop. Both are accessed by RS232.

To reduce the weight and space consumption in the upper body, the humanoid robot is not equipped with standard connectors. All interfaces can be accessed by pin headers on the PC104 board. The compact flash card slot is available from the robot's front. For interaction with the user the robot provides 8 LEDs and 4 pushbuttons.

Microcontroller board. The microcontroller circuits used on the robots are specially designed boards based on Renesas MCUs (Micro-Controller-Unit). They differ significantly in performance.

On the four legged robot a simple designed based on the Renesas SH2/7125 MCU (Micro-Controller-Unit) running at 50 MHz with 8k of flash-ROM and 4k of RAM is used. The main purpose of this controller is providing an interface to the servos and sensors for the onboard PC. It provides 8 analogue-digital-converters (ADC), 18 digital I/O (DIO) pins, and serial communication with the servos. Two ADC channels are hard wired to the most relevant directions of the acceleration sensor. The remaining six ADCs and all DIOs are accessible by pin headers. The onboard PC is connected by RS232, allowing a control cycle of 8 ms for the motors.

On the humanoid robot a much more powerful circuit is used. The design is based on a Renesas SH2/ 7211 MCU running at 160MHz. It is equipped with 512 kB of flash-ROM and 16 MB of RAM. It provides 8 ADCs, 20 DIOs, two independent RS485 busses for servo communication and an RS232 connection to the onboard PC. All DIOs and 3 ADC are accessible by pin headers. The scope of this board is far beyond mere interfacing of sensors and actors. Instead, the board is used to generate biped walking motions in realtime and independent of the onboard PC. Motion generation is based on ZMP-theory, inverse kinematics of the robot and online stabilization (see [6]). The control cycle time of the motion generation is currently 10 ms.

Both MCU-boards can be programmed in C and are supported by an adopted GNU toolchain. Robotis provides a toolkit for flashing new programs to the controller boards.

2.4 Discussion of Humanoid versus Four-Legged Robot Platform

In this section the similarities and differences of the presented platforms are briefly discussed and also summarized in Table 1.

The obvious difference of the platforms is the outer shape of the robots. Due to the differing modes of locomotion and differing weight of the platform, servo moters of different strength had to be chosen. Nevertheless all servo motors share a common logical protocol, allowing easy transfer of know-how when changing the platform.

Both platforms share a similar structure of the computing and sensing capabilities (see Fig. 5). The major difference is the microcontroller (MCU) board, which is just a "smart interface" on the four-legged robot while providing a reasonable amount of computing power on the humanoid robot. The onboard PC is the same on both platforms allowing an easy transfer of high-level software applications between both robots.

Except for the MCU boards only standardized devices and off-the-shelf components have been used for the robots. This allows for an easy upgrade of single components. The use of servo motors with a bus (instead of servos with individual connections to the MCU-board) allows for an easy expansion of the robots motion capabilities.

Table 1. Comparison of biped and four-legged platform

	humanoid robot	four-legged robot
Servo motors	18 RX28 3 RX64	15 AX12
Servo bus	RS485	TTL
Servo bus protocol	Robotis Dynamixel	
Main computer	PC104 Standard Board Geode CPU, 500 MHz up to 1 GB RAM	
Interfaces	VGA, Keyboard, 2 x RS232, 2 x USB2.0 100MBit LAN, WLAN, Audio	
Microcontroller board	SH2/7211 MCU 160 MHz 512 kB Flash ROM 16 MB RAM	SH2/7125 MCU 50 MHz 8 kB Flash ROM 4 kB RAM
Digital I/O ports	20	18
ADCs	8 (3 free to use)	8 (6 free to use)
Camera	Philips SPC1300	Philips SPC900 (to be replaced by SPC1300)
Inertial sensors	3DOF acceleration sensor in torso	
	3DOF gyroscope in hip	1 gyroscope in torso, 1 in head
Batteries	4 or 5 cell LiPo	3 cell LiPo

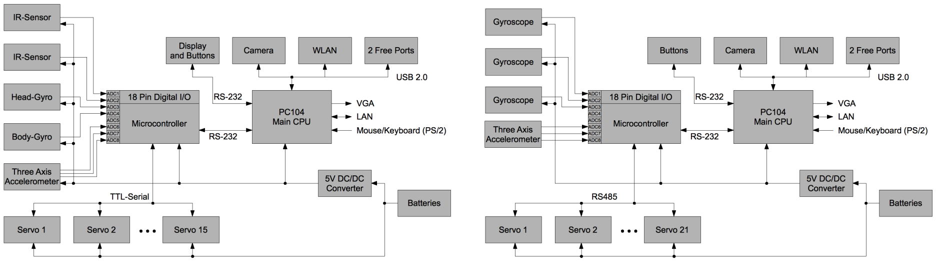


Fig. 5. Left: Structure of the four legged robot's components. Right: structure of the humanoid robot's components.

3 Results and Potential Applications

Several motions of the new four-legged robot have been demonstrated already. Videos are available on a dedicated web page[3]. With the humanoid robot platform a number of excellent results have been obtained like fast and stable humanoid walking, highly versatile robot motions (e.g. autonomous getting up from a fall, autonomous backheel kick, versatile kicking motions for robot strikers as well as jumping motions for goal keepers), fast navigation in a dynamic environment etc. Videos are also available from dedicated web pages[4].

Therefore the described platforms seem to be well suited for various different research topics in the area of animaloid or humanoid robotics. Primarily four-legged respectivly biped gaits can be investigated. Especially the biped gaits and their special demand for stabilization can be examined in detail and various different control algorithms can be developed using the existing sensors. Experiments in the authors group have shown that the kinematic of both robots is well suited to develop stable and fast walking motions. During construction of the robots it has also been paid attention to enable a wide variety of additional motions for getting up and interacting with the environment.

The new four-legged robot is equipped with acceleration sensors in the head, thus providing sensor information which can be used to research ways to stabilize the camera system during walk motions. Due to the modular design it is also possible to extend the hardware with additional sensors (e.g. force sensors) for advanced investigations.

For research in human-robot-interaction the outer appearance of the robots has been choosen to be pet-/human-like. This is supported by special motions which imitate human emotions and the legged locomotion, which permits the robot to operate in human environment. Those attributes lower the inhibition threshold for human-robot-interaction for people with low affinity to machines.

4 Conclusions and Outlook

Two prototypes of new autonomous, four-legged and humanoid robots have been presented. These robots are ready to program and have demonstrated a high capability and large variety in motion, sensing and onboard computing abilities. As they are based on an open, modular and reconfigurable software *and* hardware design they are highly interesting platforms for a wide range of research and educational projects. The modular design also facilitates repair and maintenance.

The robots can currently be obtained for evaluation by other researchers at a moderate cost from the authors.

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