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# NimbRo-OP Humanoid TeenSize Open Platform

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***Abstract*—Humanoid robots are increasingly popular as a research tool, which is motivated by the versatility of humans to locomote, to communicate, and to perform arbitrary tasks in unstructured environments. Progress of humanoid robotics is, however, severely inhibited by the lack of affordable robust platforms with a sufficient diversity of capabilities. In this work, we present a first prototype of a TeenSize humanoid robot, targeted to close the gap between small, low-cost KidSize robots with limited capabilities and adult-sized, but extremely cost intensive research platforms. The NimbRo-OP prototype is large enough to act and interact in everyday human environments and is equipped with enough torque to investigate dynamic bipedal locomotion, ample computing power, and a wide field-of-view. The prototype is available at low acquisition cost and can easily be modified or repaired. The hardware CAD files and a first version of the operating software have been released open source.**

## I. INTRODUCTION

Research in the area of humanoid robotics is motivated by the idea that the humanoid form with hand-like manipulators, bipedal walking capabilities, and multimodal communication skills is beneficial for the versatility, mobility, and operability of service robots employed in the immediate environment of humans. The use of the same tools and control panels that were designed for human hands, the ability to navigate in terrain inaccessible for wheels, and the skill to understand and perform speech and gesture-based communication, could be the crucial advantages of flexible and reliable service robots of the future over specialized and constrained machines built for a particular purpose. However, the lack of low-cost, low-maintenance, and robust bipedal platforms of a reasonable size severely slows down scientific progress in this area.

Inspired by the success of the recently introduced KidSize DARwIn-OP, we developed a first prototype of a TeenSize humanoid robot and released it as an open platform. The NimbRo-OP bipedal prototype is easy to maintain and to modify. Given the open-source construction plans, the prototype can be reproduced and assembled at low cost from commonly available materials and standard electronic components. The robot is equipped with enough computational power and torque to cover full-scale operation from image processing over trajectory planning down to the generation of dynamic full-body motions. It is large enough to be able to interact with human-scale environments and is therefore suitable to support research in relevant aspects of humanoid robotics.

The remainder of this paper is organized as follows. After reviewing related work, we provide detailed information about the robot hardware in Section III. The software developed is described in Section IV.

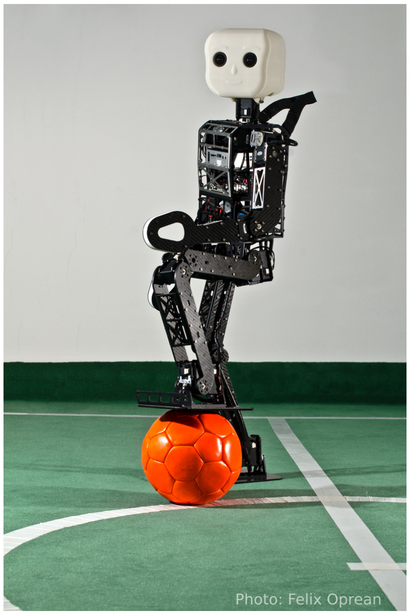
Photo: Felix Oprean

Fig. 1. NimbRo-OP first prototype.

## II. RELATED WORK

As the research on humanoid robotics enjoys increasing popularity, several commercially available products suitable as research platforms appeared on the market. The available bipedal robot types are polarized in either affordable, small-sized robots that fit in the KidSize category of RoboCup, or extremely cost-intensive adult-sized humanoids, produced mostly in Japan and South Korea.

Entry-level construction kits including and similar to the Bioloid merchandised by the Robotis Inc. company, are targeted at the hobbyist market with a price affordable for private buyers. While effort has been made with enough success to legitimate competition participation [15], the very limited capabilities of these construction kits make them suitable for entry-level research only, as they lack the strength to carry a reasonably-sized processing unit and sufficient electric power supply.

With a body height of approximately 60 cm, the Nao robot [6] produced by the company Aldebaran Robotics was the first European bipedal standard platform to appear with a strongly reduced size and an affordable price for research institutions to purchase a few copies. In 2007, Nao replaced Sony's quadruped Aibo as the robot being used in the Standard Platform League of RoboCup. Nao has reliable walking capabilities combined with a rich set of features, such as a dual-camera vision system, graphical motion authoring and debugging tools, an SDK for free programing of software com-

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ponents, a WiFi interface, and voice I/O. Being a proprietary product, the possibilities to repair or customize the hardware are very limited. Aldebaran, however, offers a time-limited warranty.

The recently introduced DARwIn-OP [7] is a strong alternative in the KidSize sector. In 2011, the year of the official release, team DARwIn won the KidSize competitions of RoboCup and successfully demonstrated the potential of this hardware, that was developed in the Robotics & Mechanisms Laboratory (RoMeLa) of the Mechanical Engineering Department at Virginia Tech. In contrast to the commercial product of Aldebaran, the DARwIn-OP has been designed to be assembled and maintained by the owner, but a fully operational version can be ordered from Robotis for a price that is comparable to the Nao robot. Most importantly, DARwIn-OP has been released as an open platform. Software and construction plans were made available for public access, which will undoubtedly leverage a wide spread of the hardware into research laboratories worldwide. Community-based improvements of the hardware and software can be expected to raise the quality of the platform in the future, as more and more experience and solutions to common problems are integrated.

Fujitsu Hoap and Sony Qrio [9] are further examples in the smallest size class, but their production has been discontinued.

The limitations of the KidSize robots lie in their size. Interactions with humans and objects in the environment require the construction of miniature experimental setups. Falling, an undesired but inevitable consequence of walking on two legs, is a negligible problem for small robots. Larger robots, however, can suffer destructive damage as the result of a fall. Consequently, reacting to a fall on software and hardware level to avoid damage is going to be a crucial feature of future robots that move freely in unstructured environments and its research requires easy-to-repair robots with adequate size and weight.

Aside from the KidSize robots, a number of AdultSize commercial platforms are available with sizes larger than 120 cm. The most prominent models are the Honda Asimo [8], the HRP [10] series developed by AIST and produced by Kawada Industries in Japan, the Toyota Partner Robot [14], and Hubo [12], developed at KAIST in South-Korea. The extremely high acquisition and maintenance costs of these robots make them unreachable for most universities and thus unavailable for many research efforts. Furthermore, these robots are not designed to survive falls, neither are they easy to repair. The necessary safety precautions in form of mobile suspensions increase the time and effort needed to conduct experiments and limit them to low-dynamic situations.

The NimbRo-OP platform closes the gap between affordable, but too small, and large enough, but too expensive models and combines an affordable price and low maintenance costs with the versatility and dynamics of larger humanoids.

## III. HARDWARE DESIGN

We designed the hardware by considering the following criteria. Affordable price, low weight, simple design, off-the-shelf parts, robot appearance, and reproducibility in a basic workshop. Please refer to Fig. 2 for an overview of the main hardware components.

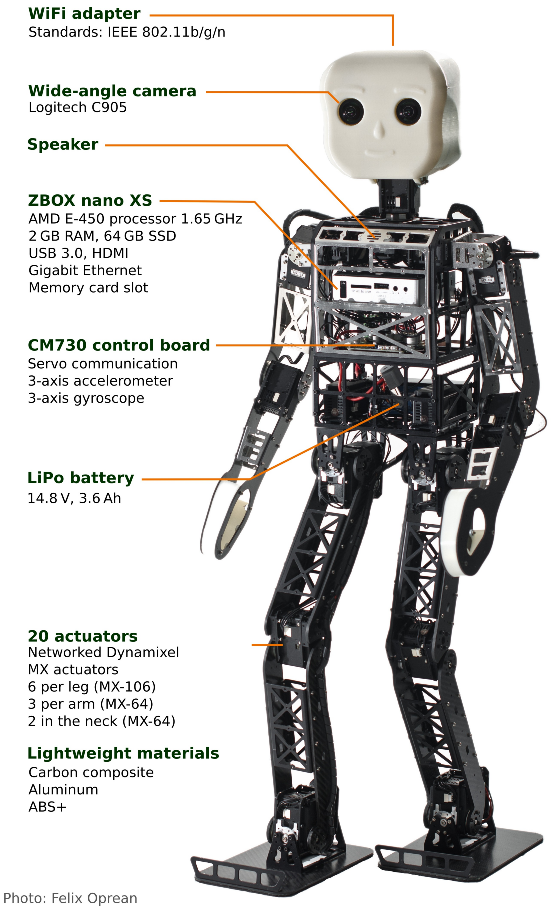

Photo: Felix Oprean

Fig. 2. Overview of the hardware components.

### A. Mechanical Structure and Actuators

NimbRo-OP is 95 cm tall and weights 6.6 kg, including the battery. Limiting the robot size to 95 cm allowed for the use of a single actuator per joint, thus, reducing cost and complexity in comparison to our previous TeenSize robots Dynaped and Copedo [11] which have two actuators per joint in each leg. We also did not use the parallel kinematic legs of our previous robots to keep the design as simple as possible.

The robot has 20 degrees of freedom altogether. Roll and pitch motors at the ankles, pitch motors at the knees, roll, pitch, and yaw motors at the hip joints, roll and pitch motors at the shoulders, pitch motors at the elbows, and yaw and pitch motors in the neck to provide pan-tilt motion for the head. The kinematic diagram shown in Fig. 3 depicts all degrees of freedom. The joints have large ranges of motion, which makes the robot very flexible.

All joints are driven by intelligent actuators chosen from the Dynamixel MX series [2] manufactured by Robotis. Specifically, MX-106 are used in the legs, and MX-64 in the arms and neck. Weaker motors were selected to actuate the arms

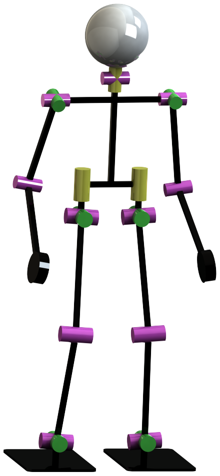

Fig. 3. Kinematic diagram of NimbRo-OP.

and neck, in order to reduce the total cost and weight of the robot.

All Dynamixel actuators are connected with a single TTL one-wire bus. The servo motors, as well as all other electronic components are powered by a rechargeable 14.8 V 3.6 Ah lithium-polymer battery.

To keep the weight low, we used light-weight materials like carbon composite and aluminum and removed all parts not necessary for stability. Arms and legs are constructed from milled carbon-composite sheets which are connected with U-shaped aluminum parts cut from sheets and bent on two sides. The torso, that harbors most of the electronic components, is entirely made from an aluminum cage, cut from a rectangular tube and milled from four sides. The head and the connecting pieces in the hands are 3D printed using ABS+ polymer. The feet are made of flexible carbon composite sheets. The kicking-toes are made from aluminum.

Most joints are equipped with a ball bearing on the backside of the actuator in addition to the bearing at the servo horn. Because this was not possible for the hip yaw joint, we added a needle-roller bearing at the horn side, as shown in Fig. 4.

### B. Electronic Components and Sensors

NimbRo-OP is equipped with a small Zotac Zbox nano XS PC, capable of running Linux or Windows-based operating systems. This PC features a Dual-Core AMD E-450 processor with a clock frequency of 1.65 GHz, providing significantly more onboard computational power than the DARwIn-OP. For data storage, 2 GB RAM (expandable to 4 GB) and a 64 GB solid state disk can be used. A memory card slot is also present. The available communication interfaces are USB 3.0, HDMI, and Gigabit Ethernet. The 10.6×10.6×3.7 cm PC case is embedded into the torso without modifications so that it is easy to exchange or to upgrade it to a different component. The head contains a small stub antenna that is part of an USB WiFi adapter, which supports IEEE 802.11b/g/n.

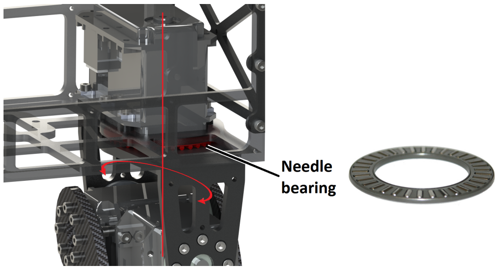

Fig. 4. Hip yaw joint: needle-roller bearing.

In addition to the PC, a Robotis CM730 board is used to maintain a high-frequency serial communication link with the servo motors. Furthermore, the CM730 board comes with integrated three-axes accelerometers and three-axes gyroscopes as sensors for attitude estimation.

We incorporated the same Logitech C905 USB camera that Robotis used in the DARwIn-OP. However, we replaced the original lens by a custom wide-angle lens that allows the robot to have field of view of up to 180°. This wide viewing angle resembles the human field of view and allows the robot to keep more objects of interest in sight. The wide-angle lens makes a large difference in primary perception compared to the DARwIn-OP and has to be modeled explicitly in the accompanying operation software (see Section IV).

For interaction with humans, a speaker has been integrated. Combined with the built-in microphone, the hardware is prepared for verbal communication. Direct interaction can also take place through three buttons mounted on the neck of the robot. Commonly, these buttons are used for robot configuration and start/stop commands. Robot status is displayed via five LEDs at the same location.

### C. Availability

The NimbRo-OP CAD files are available [3] under the Creative Commons Attribution—Non-Commercial—Share Alike 3.0 license. This allows research groups to reproduce the robot and to modify it to their needs. Fully assembled and tested robots are available from University of Bonn [4].

## IV. SOFTWARE

The hardware release of the first NimbRo-OP prototype is accompanied by a software package that provides a set of fundamental functionalities, such as visual perception, bipedal walking, and ball tracking. Out of the box, the robot is able to walk up to a uniformly colored ball and to kick it away. As a simple fall protection mechanism, the robot relaxes all its joints when it detects an inevitable fall. Moreover, when the robot is lying on the floor, it is able to stand up from a prone and supine position.

### A. Software Framework

We chose the freely available DARwIn-OP software framework [1] provided by Robotis as a starting point for software development. This framework contains a hardware interface and basic perception, motion and behavior code, which are

Fig. 5. Wide-angle lens: a) A raw camera image of a RoboCup soccer field without the wide-angle lens. b) An image from the same perspective using the wide-angle lens shows the increased field of view and the introduced barrel distortion. c) Undistorted camera image computed using Eq. 1.

mostly compatible with the NimbRo-OP platform due to the strong similarities with the DARwIn-OP robot.

We made only the modifications necessary to provide the aforementioned basic functionalities, in order to give users already familiar with this framework a head start. More specifically, the main features we added are the correction of the wide-angle lens distortion, a torso angle estimation algorithm based on the IMU in the CM730 board, a feedback stabilized bipedal gait configuration, an instability detection and simple fall protection mechanism, and key-framed get-up and kicking motions. In the remainder of this section, each of these features will be outlined in more detail.

### B. Correction of Image Distortion

The wide-angle lens used in combination with the Logitech USB camera increases the field of view to approximately 180°, but it also introduces an image distortion as shown in Figure 5. To implement a correction algorithm, we assume a simple barrel distortion model and use the following formula to compute corrected image coordinates $q$ from distorted image coordinates $p$, relative to the center:

$$q = \frac{p}{1 - \alpha||p||^2}. \tag{1}$$

The parameter $\alpha$ depends on the individual optical system. We manually determined a value of $\alpha = 8.1 \cdot 10^{-6}$ for our prototype.

### C. Torso Attitude Estimation

A well estimated torso attitude can be very useful for balance-related behaviors. We have included a roll and pitch angle estimation algorithm in the software package that we have applied to a number of different bipedal robots before. It proved to be reliable over many years of RoboCup participation. The angle estimation filter combines the angular velocity output of the gyroscopes with the angle measurement of the accelerometers and produces a low-noise, drift-free and low-latency angle estimation. Let $\phi_{n+1}$ be the angle estimated from the gravitational vector as measured by the accelerometers and $\dot{\phi}_{n+1}$ the angular velocity reported by the gyroscopes. Then, the next torso angle $\theta_{n+1}$ is given by

$$\theta_{n+1} = (1 - K_{\text{acc}})(\theta_n + \tau\dot{\phi}_{n+1}) + K_{\text{acc}}\phi_{n+1}, \tag{2}$$

where $\tau$ is the time interval between iteration $n$ and $n+1$, typically 0.01 s, and $K_{\text{acc}} = 0.01$ is a gain that determines how much the accelerometer-derived angle is taken into account. The idea behind this approach is that while the integration of the gyroscope output produces a low-noise angle estimation that suffers from drift, the angle estimated from the accelerometer is drift-free, but quite noisy, because it cannot distinguish between gravity and other accelerations occurring due to robot motion. The blending of a small fraction of the accelerometer angle into the gyroscope integration combines the good properties of each sensor type, as it "ties" the low-noise gyro integration to the drift-less signal of the accelerometers. In contrast to recursive filters, our algorithm does not introduce any lag. The gyroscope bias is calibrated at startup and then remains constant. This method yields enough precision for typical robot run times. Figure 6 shows the output of our attitude estimation algorithm during an experiment.

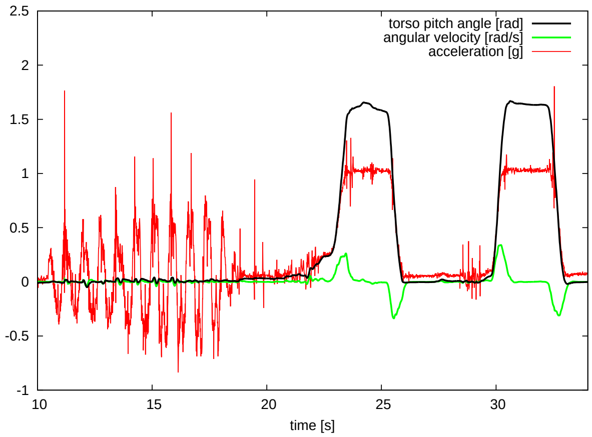

Fig. 6. Attitude estimation. First, the robot was repeatedly moved with a high frequency and a low amplitude in the sagittal direction. The pitch angle estimation remains stable despite the high acceleration. After 22 s, the robot was pitched forward twice to a horizontal position of approximately 90°.

### D. Fall Protection

The instability detection and simple fall protection mechanism we added to the original DARwIn-OP software is based on the estimated torso angle. The instability detection is implemented as a simple threshold. It triggers the fall protection reflex when an absolute angle deviation greater than 30° with respect to the upright position is detected.

The fall protection reflex relaxes all servo motors in the body such that they are free-wheeling. The most frequent mechanical damage we encountered in total during our history of RoboCup participation were broken gears in servo motors, due to high external forces opposing the motor torque. We found that relaxing the joints during falls greatly reduces the risk of breaking gears.

### E. *Gait Generation*

Due to the larger kinematic structure of the NimbRo-OP, the gait configuration had to be modified extensively to adapt the same walk algorithm to the TeenSize robot that was originally developed for the DARwIn-OP. The chosen parameters are given in Table I.

TABLE I
USED GAIT CONFIGURATION PARAMETERS.

| Parameter name | Value |
|---|---|
| x_offset | -8.0 |
| y_offset | 55.0 |
| z_offset | 10.0 |
| roll_offset | 10.0 |
| pitch_offset | -1.7 |
| yaw_offset | 0.0 |
| hip_pitch_offset | 2.5 |
| period_time | 900.0 |
| dsp_ratio | 0.1 |
| step_forward_back_ratio | 0.26 |
| foot_height | 12.0 |
| swing_right_left | 1.4 |
| swing_top_down | 0.0 |
| pelvis_offset | 0.0 |
| arm_swing_gain | 1.5 |

In addition, we made balance-related modifications to the code. When the walking pattern is executed starting from a standing posture, the first step typically induces instability. To initiate the gait, we explicitly reduce the amplitude of the first step to one half, which reasonably compensates this undesired effect and allows the robot to enter a steady lateral oscillation faster than with an unmodified step.

Furthermore, we introduced an active leaning component that modifies the ankle pitch target angle with an offset, which is a linear function of the desired walking speed in sagittal direction. The reason for this is that the robot tends to lean backwards and often even falls backwards at higher walking velocities. Fig. 7 shows the estimated torso pitch angle recorded while the walking velocity was increased slowly, ten times without and ten times with active leaning. The experiment shows that the active leaning component compensates the backward tendency and entirely eliminates backward falls that were caused by it.

Finally, we replaced the existing active balance behavior with a feedback-loop that requires less parameters and uses torso angular velocity estimations as input to apply a sagittal offset to the center of mass.

### F. *Standard Motions*

As we expect the Nimbro-OP prototype to participate in robot soccer competitions, we designed the two most important soccer motions aside from the walk and included them in our first software release. We used the already present linear key frame interpolation module of the Robotis software and configured parameters for a get-up motion from the front and the back, and a kick motion that can be executed with either leg. All three motion sequences are shown in Fig. 8.

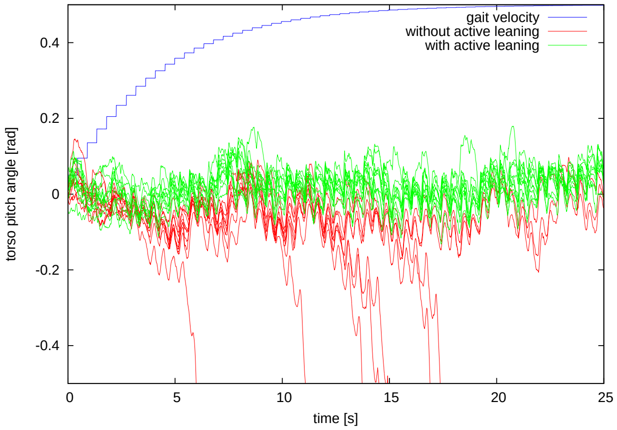

Fig. 7. Estimated torso pitch angle for ten runs without active leaning and ten runs with active leaning, while the walking velocity was increased slowly. The active leaning component compensates the backward tilting tendency and prevents backward falls.

The get-up motion is always executed some time after the fall protection has relaxed all the joints and the robot is lying in an undefined pose. Whether the robot is lying on its front or back can be detected reliably using the attitude estimation. To initiate the get-up motion, the robot first increases slowly the joint torques so that it carefully moves into a defined pose, which is the first key frame of the get-up motions. Then it triggers the corresponding get-up motion depending if the robot finds itself in a prone or supine position.

The key concept of the motion design is moving the center of mass above the feet using additional support points such as knees, elbows and hands, uprighting the torso, and finally stretching the legs [13]. This requires large ranges of motion for pitch joints, which is particularly visible for the get-up motion from the supine posture.

### G. *Availability*

Our software release has been made available [3] as a list of small patches against the original DARwIn-OP framework [1] released by Robotis. For easier traceability of changes, each added or modified feature resides in an own patch file with a header describing the change. Please visit our website [4] for further information about the NimbRo-OP platform and to stay up-to-date with the most recent changes.

## V. CONCLUSIONS

In this paper, we presented a new bipedal TeenSize robot prototype which is particularly interesting because it is large enough to be a research platform employed in realistic environments. Yet, the robot is available at low acquisition costs and is easy to assemble and easy to operate. The robot can be repaired by non-specialists, if necessary, and can be modified to suit other applications.

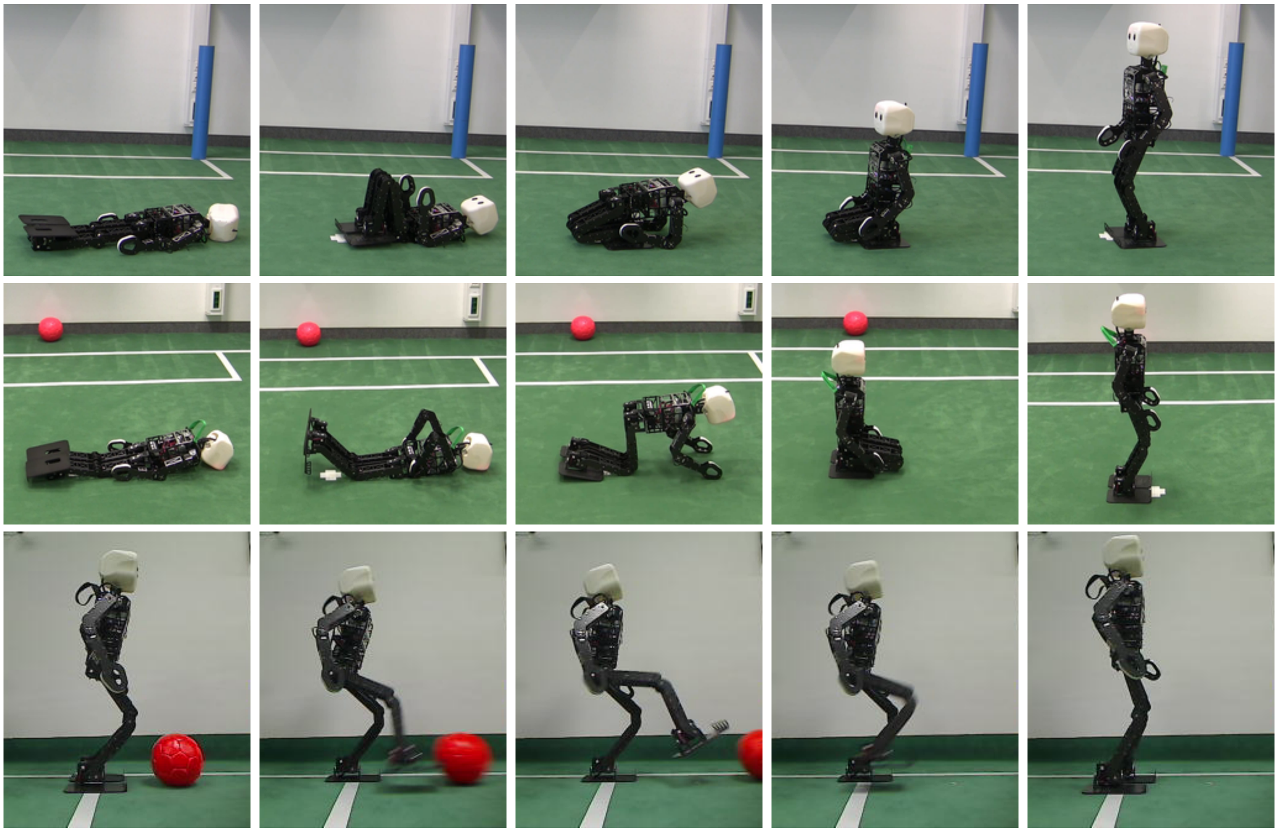

Fig. 8. The top and middle row show the get-up motions from the supine and the prone posture. The bottom row shows the kick motion.

Both, the hardware and the software, have been released open-source to support low-cost manufacturing and community-based improvements. The robot is equipped with strong actuators, ample processing power, a wide-angle camera, and a software package providing basic skills.

In future work, we are planning to improve the hardware by focusing on durability, impact resistance, and easy maintenance. We are also planning to construct an outer shell, which will not only improve the appearance of the robot, but play an important role in protecting sensitive components against damage caused by falls. Furthermore, we are going to release a ROS-based [5] software framework which will improve the out-of-the-box capabilities of the robot.

## VI. ACKNOWLEDGEMENTS

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