Multi-Humanoid Team with Embodied AI

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Abstract. We developed a new approach to the design of teams of humanoid robots. We developing teams of humanoids – rather than an individual humanoid – it becomes important to consider robustness, scalability, versatility and also development and production costs. Therefore, we used a modern approach to artificial intelligence that puts emphasis on the balance between control, electronic hardware, material, sensory system and energy in order to develop the team of Viki humanoid robots. In contrast to the top-down approach of equipping a humanoid with as many sensors, motors, power, etc. as possible, we developed a bottom-up approach to the construction of humanoids, regarding both in hardware and software (behavior-based control). The approach is shown with the development of the Viki humanoid team that won the RoboCup Humanoids Free Style World Championship 2002. By finding the right balance and relationship between these components of the system, it becomes possible to develop biped walking and other humanoid behaviors with much simpler hardware and control than is traditionally envisioned for humanoids.

1 Introduction

There are many challenges to be confronted when designing multiple humanoids that should be able to perform humanoid behaviors and interact with users and between themselves. A number of problems arise when going from the development of a single humanoid to multiple humanoids. Many of these problems are similar to the ones arising when going from one mobile robot to multi mobile robot scenarios. It becomes important to design for the emergence of the global behavior of the group of humanoids, it becomes important to work with individual differences, and it becomes important to design with a minimal requirement aspect (regarding hardware and software) in mind. We believe that embodied artificial intelligence can provide a useful starting point for the design of multiple humanoids, since this approach highlights some of the challenges mentioned above.

In order to explore embodied artificial intelligence, we developed the team of humanoid Viki robots (see figure 1). It is our working hypothesis that morphology plays a crucial role in intelligence and intelligent system. Unfortunately, in the past, many researchers have neglected the investigation of the role of morphology. In artificial intelligence robotics, many researchers looked at optimization and adaptation of control on a fixed hardware platform, and therefore optimized to a specific hardware platform only, and not to the overall problem solving behavior. With the Viki humanoid work, we would like to emphasize that optimization towards the best behavior on a global task should happen by finding the right balance between hardware, material, energy use, and software. Indeed, for the first prototype, our software is fairly simple, and becomes a primitive form of a behavior-based system, inspired by the work on behavior-based robotics [1], and our own work on using behavior-based systems for edutainment robotics purposes [2,3]. By purpose, we chose a simple form of control in order to show that it is the right bottom-up mentality in the design process that leads to the result rather than the control in isolation. Indeed, we find that only few motors and inexpensive sensors are necessary, and that a simple control is sufficient, if they are used in a bottom-up approach where all components (hardware, software, mechanics, energy use, control, etc.) are designed for the integration to achieve the overall behavior. This is viewed also to be in spirit with the embodied artificial intelligence approach presented in [5].

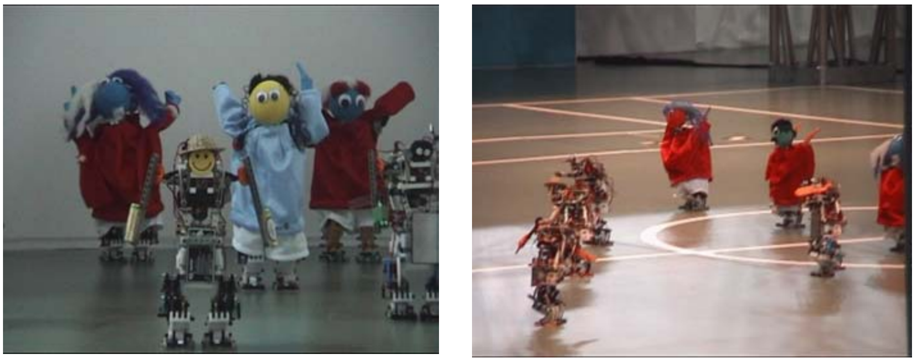

Figure 1. The team of Viki humanoid robots making dancing performance.

2 Mechanical structure

The mechanical structure of the robot is based on several simple parallel or non-parallel prismatic structures which allow us to simplify the mechanical design so, that very few actuators are needed for mobility.

In the robot 5 DC 6 Volt motors form Faulhaber, Switzerland are applied:

• **Upper Body**	∅13mm 1331 T 006	+ Gearing Head 14/1 134:1
• **Hips**	∅10mm 1016 M 006	+ Gearing Head 10/1 1024:1
• **Legs Rotation**	∅10mm 1016 M 006	+ Gearing Head 10/1 256:1 (×2)
• **Arms Shift**	∅10mm 1016 M 006	+ Gearing Head 10/1 1024:1

The first prototype of the Viki principal structure was made of ”LEGO Technics” units. Later the plastic made prototypes of hips and legs were designed and produced using facilities of the Maersk Institute for Production Technology.

Later a number of copies of the first prototype were made using CNC machinery after CAD drawings. Both CAD drawings and copies were produced using internal collaboration inside the University of Southern Denmark. For the prototypes specific plastic-made units (12 units in total) were designed to increase stability of the robot and to allow motors installation (see fig.2). The units were made so that they fit with the standard LEGO sizes, which allowed us to use a number of LEGO units in the final robot's structure where it was possible from durability point of view.

It was important to be able to use LEGO standard gearing wheels because the production of the custom-made gearing transmission could take a long time and increase the final price of the robot a lot. On all motors standard LEGO axis where installed which allow later installation of the other elements (see fig.3). But we did not observe serious problems from usage of LEGO gearing wheels, which shows that the robots structure itself does not overstress them even in the worst conditions.

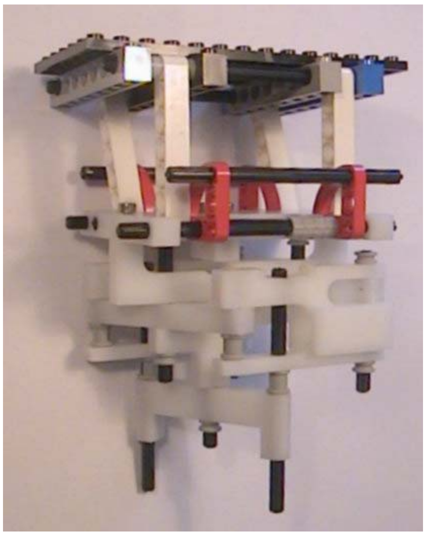

Figure 2. Plastic structure compiled

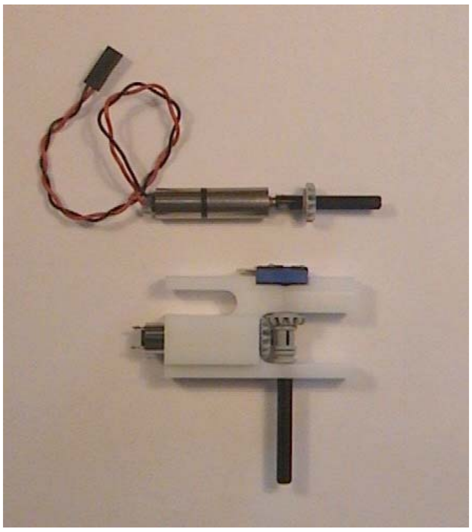

Figure 3. Typical motor's installation

It should be noted that there were some mechanical problems but most of them seems to arise from the fast prototype production (only 3 months from the first LEGO prototype to having all Viki robots ready). These minor prototyping problem experiences are used for the development of a new improved prototype Viki 2.

All the motions of the robot are assumed quasi-static on the design stage but it is possible in the later prototypes apply some dynamic motions using principles, which we introduced in our recent publication [4].

2.1 Upper body structure

The upper body structure uses one motor (∅13mm 6V DC 134:1 Gearing Ratio) for both the main weight shift and legs extraction-contraction. One non-parallel prismatic structure is used. The operation is based on combination of two pulling strings (at the left side and at the right side of the upper body) and legs structures loaded by springs (rubber bandages in the simplest case). Strings actuated by the same motor in a way that while one string is pulled in by a round pulley the other one is released with the same speed from another pulley. The properly adjusted structure works so that the main weight shifts in between two extreme positions. While the main weight is shifting it performs a very small effect on the motion of the legs (low load phase, see fig. 4). But when the extreme position is reached and the main weight is shifted, the leg extraction from one side and contraction from the other side is started (high load phase, see fig. 5).

The extraction of one leg together with contraction of the other one leads to balancing of the robot on extracted leg. The maximum possible extraction of one leg allows taking the other leg off the ground for about 2-3cm. So, it is possible to perform a step. The step action is performed by hips structure.

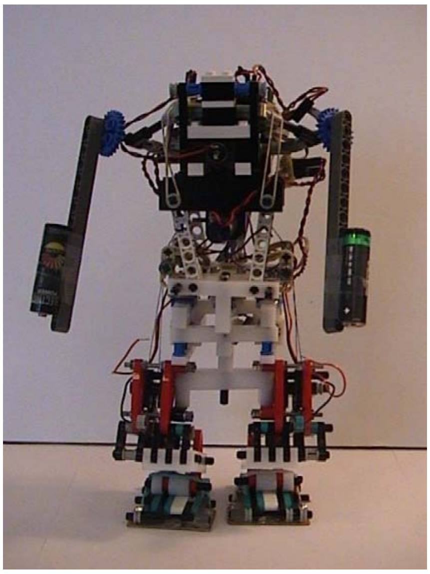

Figure 4. Low load phase

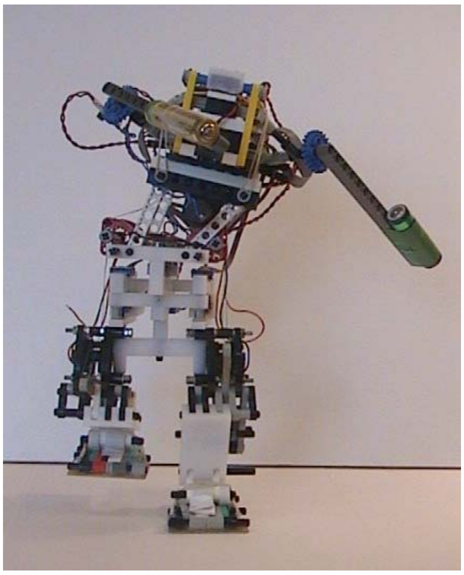

Figure 5. Height load phase

2.2 Hips structure

The hips structure uses one parallel prismatic structure (see fig. 6) actuated by one motor (∅10mm 6V DC 1024:1 Gearing Ratio) in the middle. So, depending on which leg is on the ground, the left step forward or the right step back (for instance) will be performed by the same hips action.

The length of the step is restricted by the choice of mechanical structure of the hips. The legs are not only moving back and forth but perform a curved motion with curvature depending on dimensions of the hips units. But it would be possible to design all needed units only custom-made, and not according to LEGO sizes, so that this structure could be optimized in a better way. (However, human beings use a similar hips structure.) So the final structure allows performing a step of about 1.5-2.5cm of length.

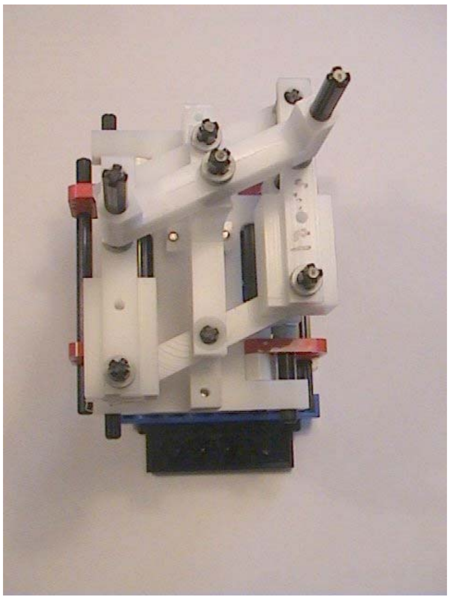

Figure 6. Prismatic structure of the hips

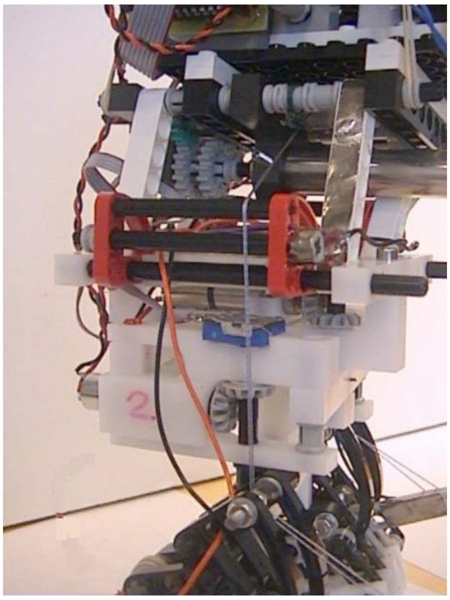

Figure 7. Actuators of the hips and upper body

Two motors for rotation of the legs (∅10mm 6V DC 256:1 Gearing Ratio) (see fig. 7) are installed in left and right hips units so that it is possible to rotate one leg for more than a half of a revolution. As a result not only the straight step could be done but also steps combined with rotation around the foot place, which turn the robot around the standing leg and also allow the ”swing” leg to prepare for the next action.

2.3 Legs Structure

One prismatic structure is used in each leg (see fig. 9). The structure is designed so that the orientation of the upper part is always vertical compared to the feet level. It means that it is possible to walk only on a horizontal surface but RoboCup competitions did not suppose a robot to move on uneven surface, which is a difficult task for any other humanoid robot.

On the figure 9 the structure of the legs actuated by string-spring system could be seen. While the pulley of the upper body pulls up the string, the leg is extracted and the spring is loaded. The rear action (the string unwinding from the pulley) leads to the contraction of the leg actuated by the spring, which was loaded before during extraction phase.

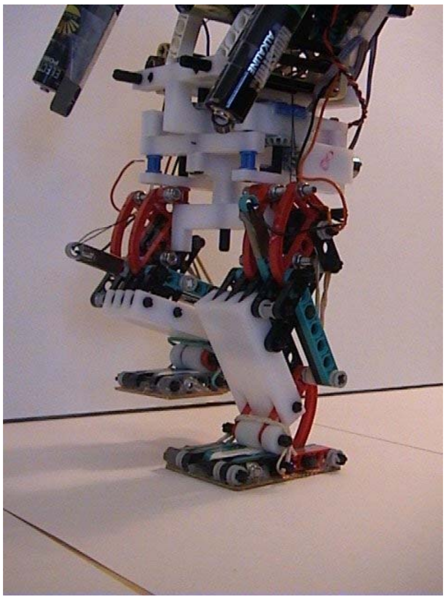

Figure 8. Balancing on extracted leg

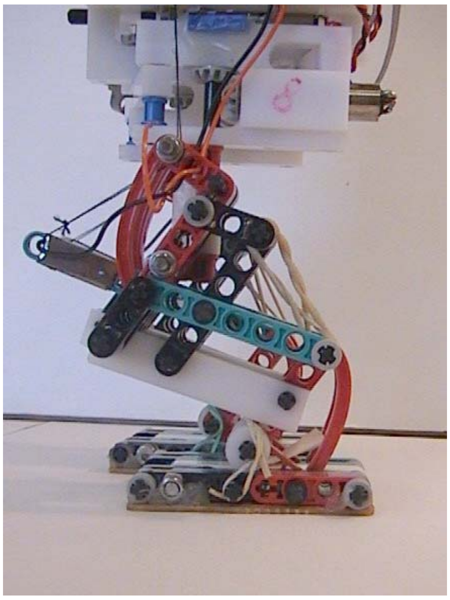

Figure 9. Prismatic structure of the legs

2.4 Arms structure

On the design stage we anticipated to use the arms like additional weight shift for fine tuning of the center of the mass position, because we did not know exact weight of the batteries/computer block, but the final structure of the robot turned out to be stable and robust enough without additional balancing weights. So, we use the arms motions more for entertainment reasons for more ”human-like” walk.

One motor (∅10mm 6V DC 1024:1 Gearing Ratio) is used to shift both arms to the same side. Two additional weights (regular 1.5V batteries) are attached to the arms to be shifted from side to side. The mechanics of the unit is designed so that shifting happens in some inclined plane compared to the robot’s upper body. As a result the ”balancing” is also made in back-forth direction for the possibility to direct the mass center positions under extreme rotated positions of the legs. There are some dangerous regions of the state space where the robot still could loose the stability without arms usage but in practice we did try to avoid such states. They are far from regular motions anyway.

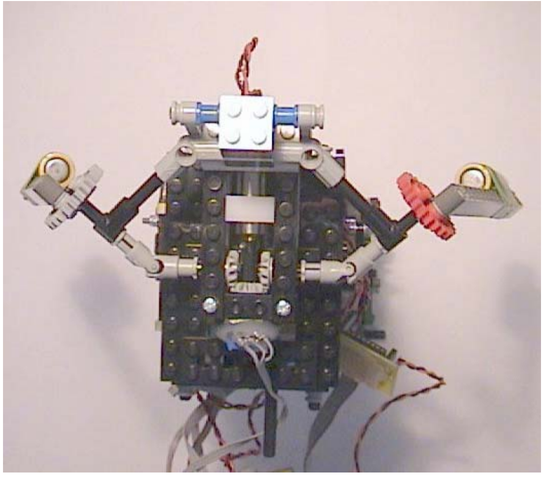
Figure 10. Arms shifting mechanism

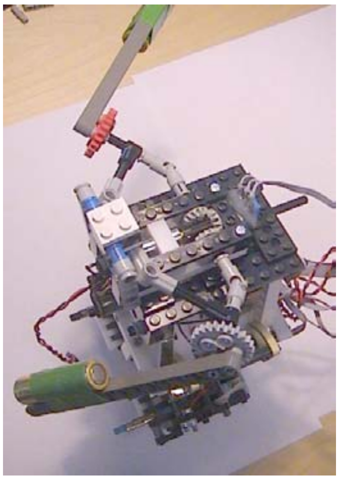
Figure 11. Balancing by arms

3 Hardware structure

To control Viki, a middle sized embedded computer was built with an AMD186ES micro controller.as the central processor. The computer which features a 512 Kb of RAM and a permanent storage space of 0.7 Mb runs an embedded version of DOS with a asynchronous serial port as standard out and standard in. This allows for easy testing and prototyping since all the benefits of a file system and an advanced operating system is incorporated in Viki. Viki is powered from two 3.6 V Ion Lithium Polymer cells with an energy density of 920mAh connected in series. This power supply allows Viki to run for half an hour having the computer consuming 66% of the energy.

Because of a lack of I/O pins on the main processor on Viki, all sensors and actuators were built as passive slaves attached to an I2C bus with the main processor programmed as an active master.

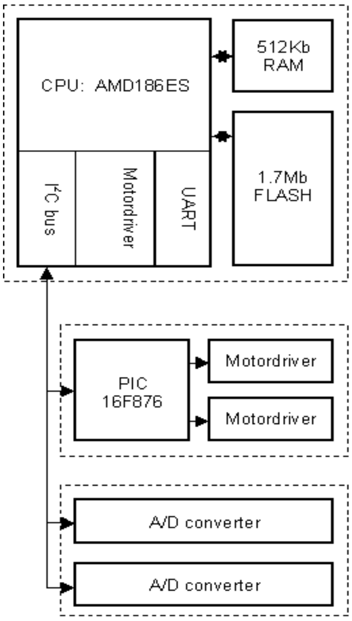

Figure 12. The electronic hardware diagram

3.1 CPU

The CPU in Viki is a AMD186ES micro controller which essentially is an Intel 186 clone wrapped in a micro controller layer that amongst others offer two UARTS, timers and several bi-directional I/O pins. The micro controller is supported by 512Kb of working RAM and approximately 0.7Mb of FLASH disk for program storage and file-creation. The system runs an embedded DOS compatible with the IBM DOS allowing for program-development on a PC with any DOS compiler.

The I2C interface to the CPU was implemented in software on top of the DOS and got therefore limited to a bandwidth of 0.1 kHz.

The CPU is commercially available under the name TinyPC186.

3.2 Power supply

Viki is powered by two lithium-ion polymer batteries with a voltage of 3.6 volts connected in series to offer a total of 7.2 volts for use. These 7.2 volts are converted down to 5 volt for supplying the CPU and its supportive logic while all 7.2 volts are used for driving the motors. Since all power is drawn from the same source precautions had to be taken that the CPU will not reboot due to a current sink created by the motors. To avoid this, a simple current limiter was introduced as shown in figure 13.

All current consumed by the motors had to pass through a 10Ω power resistor allowing a maximum of 700mA to be consumed by the motors. This will ensure that there at any time will be current left for the CPU when operating with a reasonably charged battery.

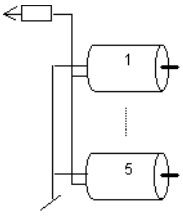

Figure 13. The current limiter.

3.3 Motor control

To control the motors used for actuating Viki's legs, hips and upper body a distributed motor control was implemented outsourcing the workload of maintaining speed and direction of the motors. A PIC16F876 micro controller was programmed to act as an I2C slave that could receive information on and maintain the speed and direction of four motors. If the CPU needs the motor for left leg to rotate counter clockwise, it would send a command to the PIC16F876 that makes the motor do so. This is a very low cost and flexible solution that allows for any number of "outsourced motor control" to be attached to the bus. For Viki only a single was needed.

As shown in figure 12 the CPU controls a single motor driver internally by using four of the I/O pins available. (This is the case due to recycling the control architecture from a previous project.)

Both solutions, the outsourced and the internal, were using the L293D, a full H-bridge motor driver with internal protection diodes, to drive the motors allowing applying ±7.2 volt to the motors.

3.4 Sensors

Viki needs input from its joints to ensure a stable motion. To aquire this information a linear potentiometers was built into the hips to give a continuous signal monitoring the hips displacement – which leg is forward – and on in each leg to monitor the legs rotation around the vertical axis.

To monitor the displacement of the upper body two extremity switches made from aluminium foil was mounted on the hips so that when the upper body has reached an extreme the switch closes and conducts. The same kind of switches were mounted in the knees to signal whenever a leg is fully extended. All these signals were multiplexed and the combination of switches unambiguous tells what substate of a step Viki is in.

A belt of eight infra red (IR) sensors was developed that vould allow Viki to sense the direction, limited to $n \cdot 22.5°$ quantizations, to a source of IR light. The sensors were interfaced to a PIC microcontroller that performs signal conditioning and calculations.

Since the flexing of the legs is done by rubber bandages and extraction by displacing the upper body thus pulling a string, the legs lacks a rotational axis to drive a potentiometer. The same is true for the displacement of the upper body. To a certain extend this does not matter since walking only requires the legs to flex and extend within certain limits and the upper body to stay within certain limitations as well, why two extremities sensors was implemented. Each extremity sensor was formed by two simple voltage dividers as shown in figure 14 that would offer a signal of either 5V with no switches closed, 3.3V with S1 closed and 2.5V with S2 closed.

For the legs the switches (S1 for the left and S2 for the right) was made from guitar strings being pressed on against a piece of conductive tape when the leg had extended close to its limit and for the upper body the switches was made from two LEGO bricks wrapped in conductive tape. For both the upper body and the legs the switches was placed so that Viki could impossible close both S1 and S2 at the same time.

All six feedback values was converted to an eight-bit value using the PCF8591 analog-to-digital converter from Philips interfaced to the CPU via the I2C bus.

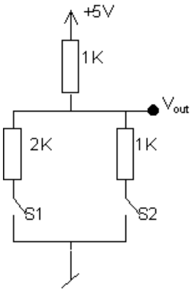

Figure 14. The simple voltage divider.

3.5 Performance

The design of the control architecture and the actuation of the body allow Viki to operate for approximately half an hour before a recharge is necessary. Simplifying the CPU further to an even more simple architecture as the current one consumes about 2/3 of the total power dissipation may increase this significantly. In contrast to that an even simpler solution with a PIC micro controller would consume only 7% of the total power dissipation.

4 Software structure

The algorithm, we developed to control Viki, was a behavior-based algorithm (see figure 15). The first set of behaviors we developed is the one for ***primitive*** behaviors. In the realization of this humanoid software, both because of theoretical issues and of the partial unreliability of the input-output system, we had the need define such primitive behaviors in a very 'molecular' way. Basically, we identified each single movement (or fraction of movement, if you prefer) as a behavior. It is to be noticed that, all the behaviours we describe in this section, were implemented one-by-one and carefully tested on the machine, step-by-step.

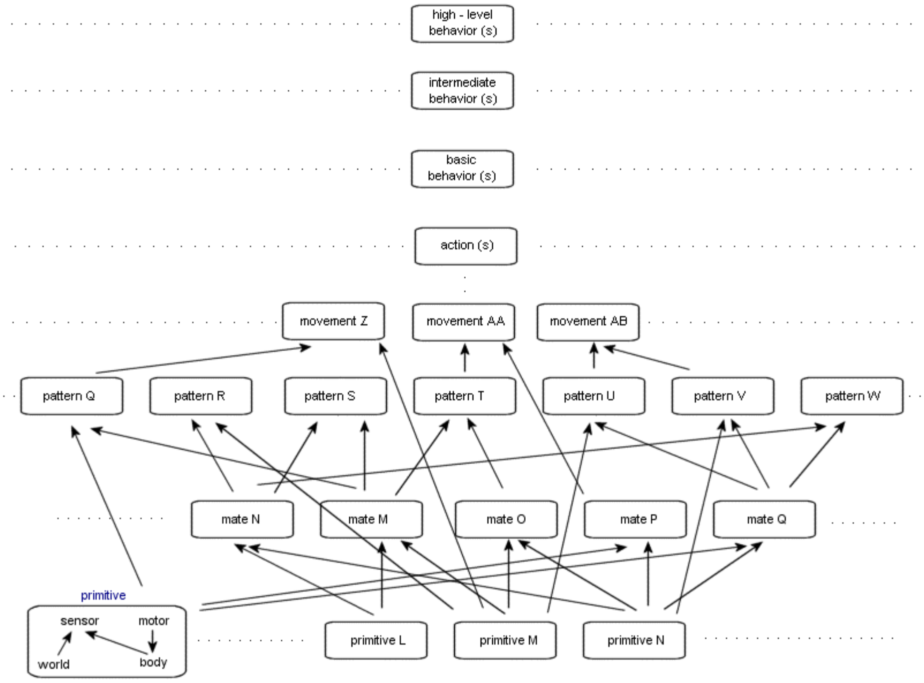

Figure 15. The software structure of the behavior-based control for the Viki humanoid robots. The different layers have increasing behavioral complexity from bottom up.

After the primitive behaviors layer, the second layer was drawn. In this layer we tried to combine as many as possible significant and compatible couple of primitives, the ***mate*s**. When talking about two behaviors (in this case primitive ones) we do not intend that they have to belong to two different input-output systems, but they can also be a proper combination, of the same one. As an example, the two behaviors (i.e.: a mate) could be: (A) '*move arms to the center'*, plus, (B) '*move arms to the left'*.

The third layer of behaviors is the ***pattern*s**. A pattern can assemble together both two single primitives, or single mates, or a primitive plus a mate. When creating a pattern we applied the same criteria of significance and compatibility used to build the mates. Of course, in humanoids, a pattern for the upper-body control is built in such a way that balancing the body is top priority. Therefore, while '*moving the upper-body from far left to the center'* can be done by (A) Move upper-body from the far left to left; (B) Move upper-body from the left to center; (C) Move arms to the center, a different sequence, or pattern, like (C, A and B) would bring the robot in a very unstable state. This is when the robot body is still on the left side and the arms move to the center, therefore loosing their function of counterweight.

After this second step, a further behavior level, the ***movements*** one, was realized. A movement can be any possible sequence of *primitive* + *mates* + *pattern*s. For example, in the *'lift the left leg'* routine, one of the most simple and reliable ones we've built, we already had many more routines than we expected. They were (we here suppose the upper-body is known to be on the left): (A) Move upper-body to the left touch sensor off; (B) Timer Start; (C) Move upper-body T milliseconds (i.e. to the center); (D) Timer and Motor Stop; (E) Move arms to the center; (F) Move arms to the right extreme; (G) Move upper-body to the right touch sensor on; (H) Timer Start; (I) Move upper-body right for T milliseconds. (i.e. lift the left leg); (L) Timer and Motor Stop. They are ten in total!

Once the movements layer was ready, we moved on to the ***actions*** level. Again, an action can be any possible sequence of *primitive* + *mates* + *patterns* + *movemen*t. For example, an action can be the (A) lift the left leg described above, plus, (B) move hip left.

By combining movements (and, of course, their sub-categories) we, finally, reached the ***basic behaviors*** level. A basic behavior could be the sum of the behavior just described, plus, a *'move the left leg down'* mate (i.e. it simply counts time before turning off one motor). The resulting basic behavior is *'one step forward left'*.

By assembling basic behaviors (and their sub-categories) we could then obtain ***intermediate behavior*s**. For example, *'one step forward left'* plus *'one step forward right'* produces the *'walk forward'* intermediate behavior. Once reached this point, the game is done.

Indeed, we only needed to link intermediate levels (and their sub-categories) into chains to construct ***high-level behaviors*** by which we can obtain beautiful, efficient and coordinate acts such those of the twelve humanoid robots dance, rewarded as the best free style show in RoboCup 2002. We consider this control architecture as very easy to design and to handle, as well as, very encouraging if thinking at the developing time (i.e.: time spent on reconfiguring the behaviors) vs. richness (i.e.: number of different behaviors obtainable) relationship.

5 Discussion and conclusion

For a future development of Viki, we envision different issues to be touched upon. The controller for Viki could be simplified further now the initial experiments have been performed and we have more experimental experience with Viki. If the controller was replaced by a even smaller one, for instance a Microchip PIC or one from the Atmel Mega-series, the power consumption could be decreased from 66% to 7% thus prolonging the operation time from 0.5 to 4 hours.

Communication should be introduced allowing the Viki's to communicate or to be remote controlled or monitored. For these purposes, we have experimented with both Bluetooth solutions and various ad hoc RF solutions. For the purpose of providing Viki with some kind of vision to distinguish between comrades and obstacles, some projects utilizing a 256 greytones camera are being conducted at the moment.

Further, the current Viki humanoid robot is not able to walk on inclined surfaces. Only few biped robots in the world are able to walk on inclined surfaces with small inclinations [6]. We believe that after some years, our next prototype(s) will be able to perform this action as well because simplified leg structure leaves more space and possibilities for implementation of other systems like active balancing-contact force detection for identification of the surface inclinations.

We developed the Viki humanoid in order to show the importance of a bottom-up approach to the design of humanoid robots. In such an approach, one should look at finding the right balance between hardware, software, mechanics, material, and energy use. Our experiments show that we were able to win the RoboCup Humanoids Free Style World Championship 2002 with such an approach, even though / because it resulted in a much more inexpensive design than the competitors, and because it resulted in the focus on achieving the overall behavior by an interplay between the necessary components. In general, we hope that this and other similar experiments/results can open a discussion in the scientific community regarding the importance of morphology in intelligence and intelligent systems.

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