Sony QRIO

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Contents

Abstract

This chapter introduces QRIO, a small bipedal humanoid robot developed by Sony Corporation for home entertainment use. The key concept consists of two elements: “motion entertainment” and “communication entertainment,” for which a lot of cutting-edge technologies were developed. The hardware including Intelligent Servo Actuator (ISA) is designed so as to embed many joints, sensors, and processors into a small size. Its motion control system including a real-time

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zero moment point (ZMP) equation solver, adaptive controls against perturbations, and protective reaction in falling over is computationally lightweight as well as highly generalized. Motion editing software for the control system is also provided to facilitate content creation. For autonomous behavior control, a lot of intellectual functions including space perception, face recognition, and speech recognition are developed and are integrated in the autonomous behavior control architecture. QRIO was not commercialized, but contributed to a lot of corporate branding activities using these functions.

1 Synonyms

- *ZMP (zero moment point)*: The point on the ground at which the moments generated around the horizontal axes by the robot motion are zero.
- *Support polygon*: A minimum convex polygon that includes all the contact points of the robot with the ground.
- *ZMP stability criteria*: A theorem stating that a motion pattern becomes dynamically consistent with the equation of motion when the ZMP calculated from it exists inside the support polygon.

2 Introduction and History

QRIO is a small bipedal humanoid robot developed by Sony Corporation intended to be used for future home entertainment. The concept consists of two elements: "motion entertainment" and "communication entertainment." To achieve high-quality motion entertainment in small scale, highly stable but computationally lightweight motion control system is developed, which is coupled with motion editing software that allows creators to design motions easily without special knowledge about the control algorithm. To realize communication entertainment, leading-edge visual and auditory recognition technologies are developed and are integrated into the autonomous behavior control architecture. In the QRIO's development history, challenges to enhance these two elements have been repeated in both hardware and software design.

QRIO originates in the SDR (Sony Dream Robot) project that started in 1997. This project aimed at realizing a small bipedal humanoid that can entertain people in two ways mentioned above and developed some prototypes such as SDR-0, SDR-1, and SDR-2. The third prototype SDR-3X shown in Fig. 1 was unveiled in November 2000 in ROBODEX 2000 [1, 12]. It is driven by Sony's original actuator named ISA (Intelligent Servo Actuator) [9] developed for SDR series to realize high power/weight ratio, connectivity based on a serial communication bus, and modularization of a motor, a reduction gear and servo control circuits. It is also

Fig. 1 SDR-3X, the origin of QRIO

equipped with a monocular camera and microphones in the head. SDR-3X achieved dynamic bipedal walking using motion patterns calculated off-line based on ZMP (zero moment point) stability criteria. It also performed some gymnastic motions on the floor, para-para dances (Japanese modern dance with quick steps), and football performances using color tracking and operations via simple voice commands. These functions are implemented under OPEN-R [7], Sony's standardized robot architecture to integrate software and hardware modules.

SDR-4X, which was released in March 2002, is an advanced model whose adaptation and recognition abilities are enhanced [5, 10]. It is controlled by a newly developed "real-time integrated adaptive control system," where walking patterns are generated online and in real-time and are stabilized even on an irregular terrain and under disturbances by using accelerometers, gyros, and force sensors. A stereo vision system is implemented in its head, which realized facial recognition and navigation while avoiding obstacles [17]. Multi-microphones are also installed in its head, which enabled sound direction estimation and speaker identification. Singing voice synthesis with vibrato is also developed, which realized an a cappella performance.

SDR-4XII was released in March 2003, and its safety capabilities were improved [11]. It can cope with one of the most important issues for biped walking robots – falling over. It can also detect other situations such as tucking objects in joints and being lifted up and make protective reactions against them. Recovery functions from these irregular situations are also implemented. As for intelligent capabilities, functions for map-building, self-localization, and onboard voice recognition of large vocabularies are introduced. In September 2003, SDR-4XII was renamed QRIO [2], which stands for "quest for curiosity." QRIO was announced to the public as Sony's Corporate Ambassador and symbolized Sony's continuous quest and curiosity for technological innovation (Fig. 2).

Fig. 2 QRIO (SDR-4X)

In December 2003, an enhanced QRIO capable of "integrated motion control for walking, jumping, and running" was announced [3, 16]. A control theory beyond the standard ZMP stability criteria was developed to cope with motions including flight phases, which makes QRIO the world's first running humanoid robot as recorded in Guinness Book of World Records 2005 [6].

In September 2004, an enhanced control system for a biped walk called "natural gait control" was announced [15], which allows QRIO to walk using the edges of its soles to achieve more natural and humanlike gaits with wider stride and faster pace. At the same time, the path planning ability was improved to cope with 2.5D maps, which enabled going up/down stairs autonomously.

QRIO had been performing significant roles as a corporate ambassador in innumerable events. QRIO was also appointed as UNESCO's science messenger and promotes curiosity about science and a love of peace to children all over the world [4]. Although there had been a tremendous public response to these activities, the QRIO project was terminated in 2006. Afterward research on relevant core robotics technologies has been ongoing in Sony [14]. The following sections overview the major technologies used in QRIO.

3 Hardware

For an entertainment robot, safety, affinity, and operability are important factors in its design. So the round-shaped design criterion is employed throughout the whole robot to not injure humans and to not be damaged by collisions with the environment. Joint structure is designed to eliminate pinch points that might trap user's hands and fingers. A round grip around the collar is designed to handle QRIO easily in home use scenes.

QRIO's major hardware configuration is shown in Fig. 3. QRIO's height is 58 cm, and it weighs about 7.0 kg. It has 38 degrees of freedom (DOF) in total. Each leg

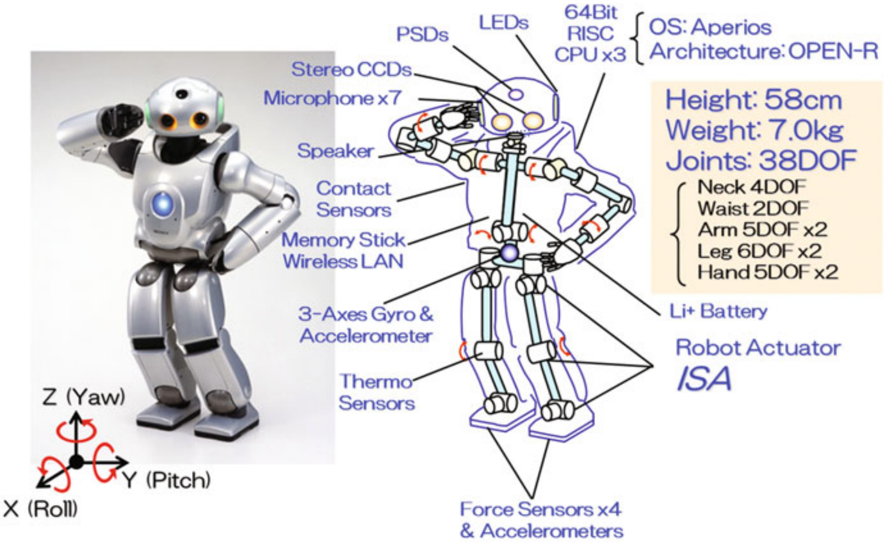

Fig. 3 QRIO's configuration

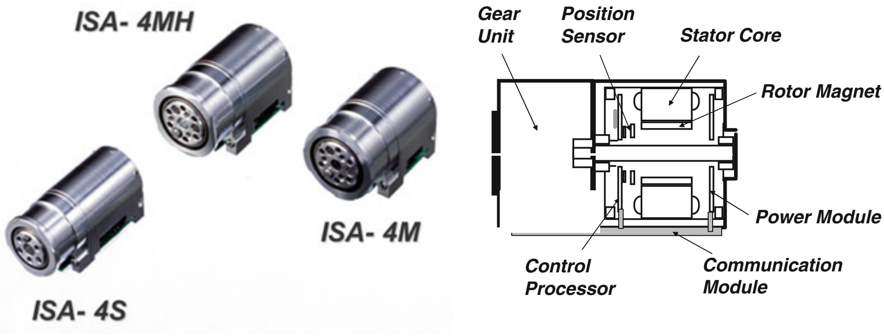

Fig. 4 ISA – Intelligent Servo Actuator

has six DOF, the waist has two DOF, each arm has five DOF, the neck has four DOF, and each hand has five independent fingers.

Major joints in legs, arms, and the waist are actuated by ISA shown in Fig. 4. ISA is an actuator that includes a motor, a reduction gear, a motor driver, a control processor, a position sensor, and a serial communication interface in one module and is designed to meet high power/weight ratio, wide bandwidth, high efficiency, and high back drivability. Three types of ISAs are developed for QRIO, whose major specifications are shown in Table 1.

For motion control, gyroscopic sensors and accelerometers are mounted on the pelvis. Each sole has four force sensors and one accelerometer in it. Contact sensors and temperature sensors are distributed on appropriate parts mainly for safety use.

Table 1 ISA's specifications

Type	ISA-S	ISA-M	ISA-MH
Rated torque [Nm]	0.6	1.4	2.2
Size (diameter × length) [mm]	25×54.5	32×52.5	32×57.5
Weight [g]	84	123	157

To realize real-time and real-world space perception, a micro stereo vision system is mounted in the head. It comprises two small color CCD cameras with about 110,000 pixels whose baseline is 50 [mm] and FPGAs to compute the disparity image that is sent to the main CPU board as a digital YUV video signal via a high-speed bus named LVDS (low-voltage differential signaling). An infrared position sensing device (PSD) is also implemented in the head and each hand. Seven microphones are located inside the head to detect a sound source and to recognize an individual speaking. A speaker in the head and LEDs in its eyes, ears, and torso are used to communicate with users and to express QRIO's internal state.

QRIO is controlled by three 64-bit RISC processors (mSDR, aSDR, and iSDR) that are operated by Aperios, Sony's original operation system. mSDR is for motion control, aSDR is for speech recognition and synthesis, and iSDR is for vision and autonomous behavior control, respectively. Actuators and most sensors communicate with them via OPEN-R BUS, a serial communication bus used in OPEN-R architecture. All the power is supplied by a lithium ion battery that enables QRIO to operate more than 1 h per charge.

4 Motion Control System

QRIO's motion control system called "real-time integrated adaptive motion control system" is developed to cope with a variety of situations occurring in home use. It has to not only perform motion patterns created off-line, but also generate gait patterns in real-time according to the surrounding environment, and stabilize them even if there were uneven terrain and unknown disturbances such as external forces. It also has to take protective motion when it falls over or something is pinched in the joints. If it is picked up, it must stop all motion safely and should restart the control when it is put on the floor again. To meet these requirements, the real-time integrated adaptive motion control system comprises the following functions.

1. Real-time whole-body stabilizing motion control
2. Terrain adaptive motion control
3. External force adaptive motion control
4. Integrated adaptive fall-over motion control
5. Pinch avoidance motion control
6. Lift-up motion control

4.1 Real-Time Whole-Body Stabilizing Motion Control

The real-time whole-body stabilizing motion control generates gait patterns and coordinates them with upper body motion while modifying a part of the whole-body motion to make it dynamically stable, which includes ZMP equation solver that is executed in real-time, online, and on board. This flexible control system is effective especially for navigation where the robot has to change footprints in real-time to avoid obstacles. Figure 5 shows a shot of the navigation realized by the combination of real-time whole-body stabilizing motion control and the stereo image recognition system.

In the later version, the ZMP equation solver is extended to cope with flight phases to realize integrated motion control of walking, jumping, and running and transitions between them (Fig. 6 left). Furthermore, in the last version, motions including point and line contacts between soles and the ground are also covered, which enabled natural gait control with a wider stride (Fig. 6 right).

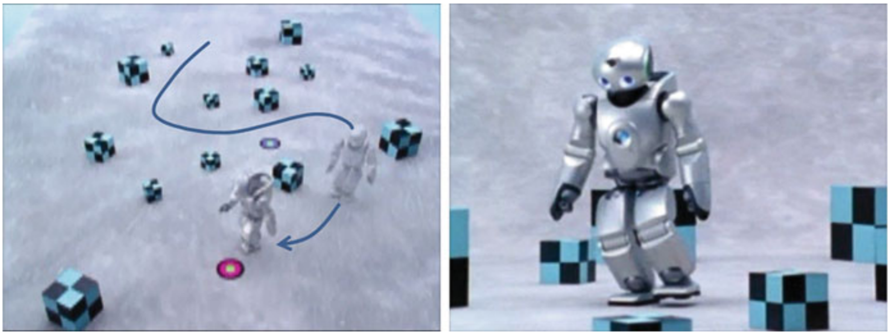

Fig. 5 Navigation using real-time whole-body stabilizing motion control

Fig. 6 Integrated motion control for walking, jumping, and running (*Left*) and natural gait control (*Right*)

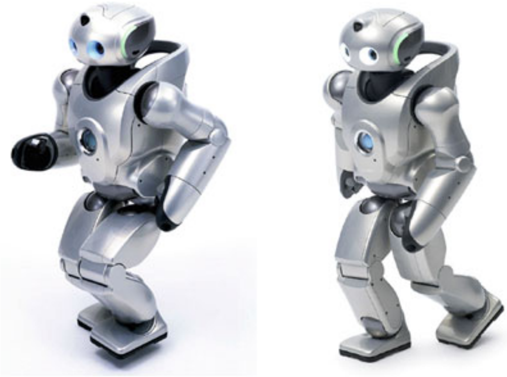

Fig. 7 Walking on uneven or moving terrain using terrain adaptive motion control

4.2 Terrain Adaptive Motion Control

Differences in level or inclination on the floor can cause a small biped robot to lose balance. The terrain adaptive motion control modifies the motion to minimize perturbation caused by uneven terrain with uncertainty that cannot be detected by visual sensors. Using redundant inertial sensors composed of accelerometers and gyroscopic sensors on the pelvis and both feet, the controller robustly estimates the posture of the robot. Force sensors on the feet are used to measure the ground reaction force and moment. The controller integrates these measurements to calculate the modified motion that is consistent with ZMP stability criteria while maintaining the ground contact state. This control enables QRIO to walk on irregular terrain with up to approximately 10 [mm] (1.7% of the body height) differences including carpets and gravels. Figure 7 shows the examples of walking onto the tatami mat from the wooden floor through their border and walking on the moving floor actuated by a motion base.

4.3 External Force Adaptive Motion Control

Perturbation can be caused by external forces as well. External force adaptive motion control estimates it by using the abovementioned internal sensors and modifies the footprint in the following steps to keep balance while maintaining ZMP stability criteria. The step length is modified in both sagittal and lateral planes. Figure 8 shows the external force adaptive reaction invoked by this control when biped walking forward is intercepted by a human hand, where the robot automatically shrinks the stride to avoid falling over.

Fig. 8 External force adaptation motion control

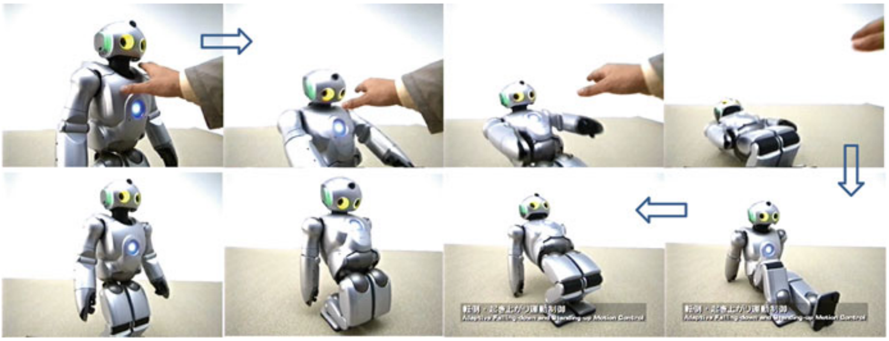

Fig. 9 Integrated adaptive fall-over motion control

4.4 Integrated Adaptive Fall-Over Motion Control

The real-time adaptive fall-over motion control treats falling over and the restitution to the normal operation. When QRIO detects the motion state exceeds the limitation of the abovementioned adaptive control, the control system suspends the executing motion and invokes the defensive reaction. It judges the direction of falling over and controls the robot to transit quickly to the secure pose depending on the direction while reducing the proportional gain of joint servoing to make the joints compliant. Here the round shape and the elasticity of the outer cover and back drivability of the actuator also play important roles to reduce the impact. After that, the controller measures the posture of the robot, transits to the nearest known posture, and executes the getting up motion from it. Figure 9 shows the example of controlled falling over and recovery from it. QRIO can cope with falling over into any direction including forward, backward, and sideways.

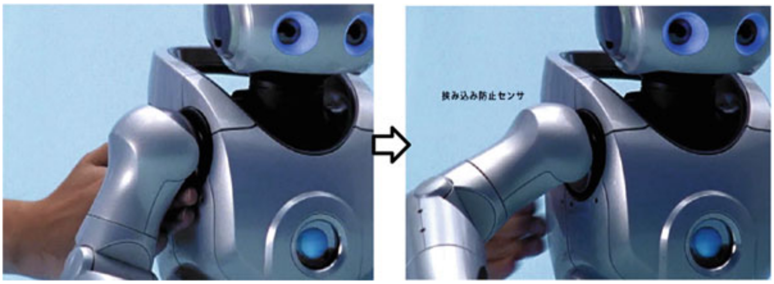

Fig. 10 Pinch avoidance motion control

Fig. 11 Lift-up motion control

4.5 Pinch Avoidance Motion Control

Pinch detection sensors composed of contact sensors are located in the vicinity of the major joints such as armpits, back of the knee and the elbow, inside of the thigh and the shin, and outside of the hip joint and the ankle. If the sensor detects something trapped there, the actuator of the joint moves to release it. Figure 10 shows the pinch avoidance reflex in the armpit.

4.6 Lift-Up Motion Control

The lift-up motion control detects if the robot is picked up and restitutes it to the normal operation when it is put on the floor again. A grip on the collar and force sensors on the feet are used to judge if the robot is on the floor or picked up. When it is picked up, the motion is halted, and the proportional gain of joint servoing is lowered to make it compliant. By pushing the button on the shoulder, the robot transits to standing pose and increases the gain and becomes ready to be put on the floor (Fig. 11).

5 Motion Editor

To produce a variety of attractive performances for QRIO, a motion editing software that can be easily used by creators is developed [13] (Fig. 12). It has timelines for

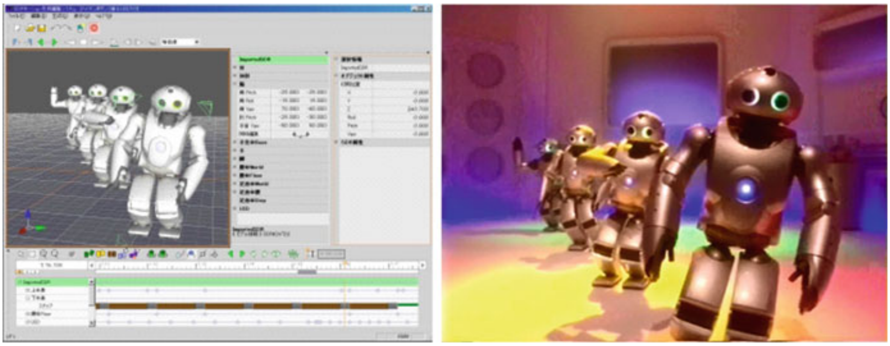

Fig. 12 Snapshot of motion editor and its corresponding dance performance

upper body motions, gait patterns, pelvis motions, and music to design synchronous performances between them. Notable feature of this software is that it includes the real-time whole-body stabilizing motion control module mentioned above that converts the designed motion to the stabilized motion expected to be executed on the real robot, which enables feasibility check of the motion considering constraints on the real robot such as joint movable range, joint velocity, and self-interference.

6 Autonomous Behavior Control System

To realize communication entertainment, autonomous behavior control system is implemented. It comprises a lot of intelligent functions and the autonomous behavior control architecture to integrate them with the motion control system, by which behaviors are properly selected and executed depending on the situation of the external world's conditions and simulated internal instincts.

6.1 Intelligent Functions

QRIO's intelligent functions are composed of technologies for real-world space perception and multimodal HRI (human-robot interaction).

For real-world space perception, the stereo vision system in the head is used, where the disparity images are computed by FPGAs based on block-matching algorithms. By calibrating the cameras beforehand, image distortion is removed and camera parameters such as focal length and the principal point are obtained. Since the algorithm easily causes incorrect matches when there is either no texture or a repetition of similar texture patterns, an additional reliability image that represents the sharpness of matching score is calculated to reject such conditions.

The disparity is first converted into 3D range data using the parameters from the camera calibration. And then randomized Hough transformation is applied to extract

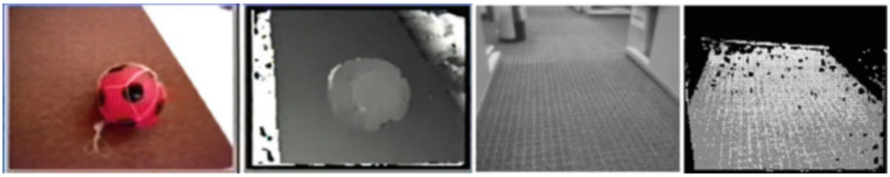

Fig. 13 Disparity image (*left*) and floor extraction (*right*) using stereo vision system

Fig. 14 Examples of intelligent functions – path planning on occupancy grid (*left*), obstacle avoidance using it (*middle*), and face detection (*right*)

plane segments, especially the floor segment where the robot can walk through. The floor plane near the feet can be estimated within an error of +/−10 [mm]. For the plane farther than 1 [m], estimation stays within the range of +/−30 [mm]. Examples of the disparity image and the plane extraction are shown in Fig. 13.

On top of the plane extractor, the environmental map using a two-dimensional occupancy grid is implemented to integrate the observations over time (Fig. 14 left). And a path planner on the map is also implemented to find a path to a goal point on which the robot can reach there without colliding with obstacles. Here the path planning problem is modeled as a graph search problem, which is realized using the A* search algorithm. In the later version, these functions are extended to cope with 2.5-dimensional world to realize going up and down stairs autonomously (Fig. 14 middle).

Regarding multimodal HRI ability, multi-face detection, and identification (Fig. 14 right), unknown face learning, sound direction estimation, large vocabulary continuous speech recognizer, speaker identification, unknown word acquisition, and text to speech synthesizer including singing voice with vibrato are implemented.

6.2 Behavior Control Architecture

To integrate above mentioned technologies and present autonomous behaviors, a behavior control architecture based on EGO model shown in (Fig. 15) is applied [8]. Roughly speaking, it is divided into five parts: perception, memory, internal state model, behavior control, and motion control.

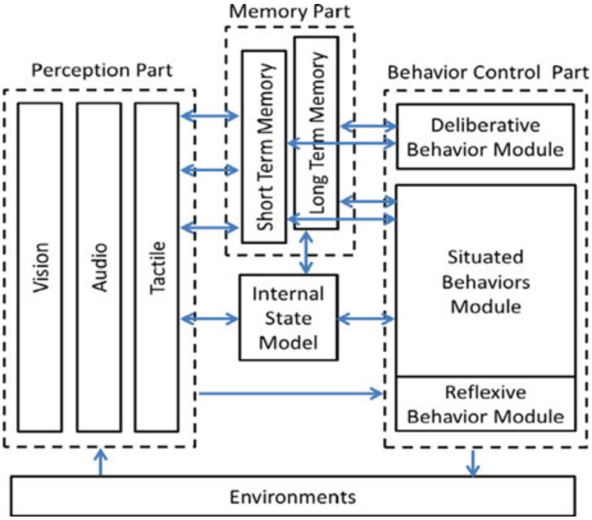

Fig. 15 Logical architecture for autonomous behavior control

The perception part has three sensor channels for vision, audio, and tactile sensors. The visual perception part deals with the spatial perception and face detection/identification. The audio perception part deals with the sound direction estimation and the speech recognition. The tactile perception part identifies several types of touching such as hit and pat.

In the memory part, there are two kinds of memories: short-term memory (STM) and long-term memory (LTM). In the STM, the position of humans and objects are memorized, which enables the robot to handle them even if they are outside of the view range. The LTM is used to remember an identified face, an identified voice, an acquired name, user’s birthday, favorite items, and so on.

In the internal state model, various internal variables alter their values depending on the passage of time and incoming external stimuli. A behavior is basically selected to keep them within proper ranges, which generates spontaneous behaviors.

The behavior control part consists of three modules: reflexive behavior control module, situated behavior control module, and deliberative behavior control module. The reflexive behavior control module deals with rapid responses to external stimuli such as falling over reaction, pinch avoidance, and lift-up events. The situated behavior control module includes many situated behavior modules such as dialogue-related ones, each of which is properly utilized for a particular situation based on external stimuli and internal drives. The deliberative behavior control modules deals with computationally heavy tasks such as path planning.

The motion control part is realized by the motion control system mentioned above, where real-time controls including adaptation to terrain and external forces are executed.

7 Summary

In this article, QRIO's development history and its technologies including the hardware configuration, the motion control system, and the autonomous behavior control system are briefly overviewed. Due to space limitation, there remains other technologies, performances, and activities regarding QRIO that could not be explained here. For details, please refer to papers and websites listed in the reference.

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