A BRIEF REVIEW OF BIPEDAL ROBOTICS RESEARCH

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Abstract

During the last few years, the number of research and development projects aimed at building bipedal and humanoid robots has been increasing at a rapid rate. In this paper, we provide a brief review of current activities in the field of bipedal and humanoid robotics. We describe both commercial humanoid projects and projects from academia. The main motivations for using bipedal robots are introduced, and we then proceed to consider bipedal locomotion as well as other behaviors. We particularly emphasize the use of biologically inspired computation methods in the field of humanoid robotics. Finally, we provide a list of a few projects in this field.

1 Introduction

Attempts at building walking machines can be traced back at least to the 1960s. In addition to research concerning bipedal robots, efforts were also made to develop monopedal (Raibert, 1986) and quadrupedal robots (Furusho et al. 1995). One of the first functioning bipedal robots was developed in the 1970s by Kato (Kato and Tsuiki, 1972). Today, there are many bipedal robot projects in the world, and the number of active projects is growing rapidly. Here, we will briefly review some of the work in bipedal robotics to date. We will mainly focus on motor skills for walking robots. However, we will also discuss behaviors that are not related to locomotion.

There exists both commercial humanoid projects and humanoid projects from academia. The latter, of course, usually operate on a much smaller budget than the former.

Clearly, in this short review, it is impossible to cover the rapidly expanding field of humanoid robotics research in its entirety. Thus, we have chosen to focus mainly on a few topics deemed particularly interesting, such as e.g. the use of biologically inspired computation methods in humanoid robotics.

In this paper, the terms *bipedal robot* and *humanoid robot* will both be used. As the name implies, the term bipedal robot refers to a robot that walks on two legs, whereas the definition of the term humanoid robot is more loose. In general, a humanoid robot is defined as a robot with some human-like features (not necessarily the ability to walk on two legs). For example, some humanoid robots consist only of an upper body or a head (see e.g. Miwa et al. 2001).

Furthermore, it is of course possible to devise bipedal robots with a *non*-humanoid shape. In fact, a prototype of such a robot was recently introduced by Sharp (Yamataka et al. 2001).

2 Motivation

There are several good reasons for developing bipedal walking robots, despite the fact that it is technically more difficult to implement algorithms for reliable locomotion in such robots than in e.g. wheeled robots. First, bipedal robots are able to move in areas that are normally inaccessible to wheeled robots, such as stairs and areas littered with obstacles that make wheeled locomotion impossible. Second, walking robots cause less damage on the ground than wheeled robots. Third, it may be easier for people to interact with walking robots with a humanoid shape rather than robots with a non-human shape (Brooks, 1996). It is also easier for a (full-scale) humanoid robot to function in areas designed for people (e.g. houses, factories), since its humanlike shape would allow it to reach shelves etc.

3 Bipedal Locomotion

The problem of providing a bipedal robot with a reliable gait is far from trivial. Thus, most work on bipedal robots to date has been focused on locomotion. In general, the motion is divided into a single-support phase (with one foot on the ground) and a double-support phase. In ordinary human gait, the length of the double-support phase lasts for approximately 20 % of the step cycle (Huang et al. 2001b). Simulations are commonly used in bipedal robotics in order to test different walking algorithms, and to reduce the risk of making costly mistakes in the hardware implementation of a robot.

One of the simplest models of a walking robot is the 5-link biped introduced by Furusho and Masubuchi (1986), and subsequently used by several authors, see e.g. Cheng and Lin (1995) and Pettersson et al. (2001). This simulated robot, which is shown in Fig. 1, is constrained to move in the sagittal plane, and has five degrees of freedom (DOF).

There exists many different formulations of the equations of motion for a bipedal robot, e.g. the Lagrangian formulation and the Newton-Euler formulation. The Lagrangian equations of motion for the simple five-link robot shown in Fig. 1 are

$$\mathbf{M}(\mathbf{z})\ddot{\mathbf{z}} + \mathbf{C}(\mathbf{z},\dot{\mathbf{z}})\dot{\mathbf{z}} + \mathbf{N}(\mathbf{z}) + \mathbf{A}^{\mathrm{T}}\boldsymbol{\lambda} = \boldsymbol{\Gamma}, \tag{1}$$

where $\mathbf{M}$ is the inertia matrix, $\mathbf{C}$ is the matrix of Coriolis and centrifugal forces, $\mathbf{N}$ contains gravity terms, $\mathbf{A}$ is the constraint matrix, $\boldsymbol{\lambda}$ contains the corresponding Lagrange multipliers, and $\boldsymbol{\Gamma}$ are the generalized forces. $\mathbf{z} = [\varphi_1, \ldots, \varphi_5, x, y]^{\mathrm{T}}$ are the generalized coordinates, where x and y indicate the coordinates for one foot of the robot.

The Lagrangian equations of motion have the advantage that the internal forces of constraint need not be explicitly represented in order to determine the motion of the robot. However, in general, the Newton-Euler formulation is computationally the most efficient, with the computation time growing linearly with the number of degrees of freedom. For a discussion of this formulation see e.g. Walker and Orin (1982).

PSfrag replacements

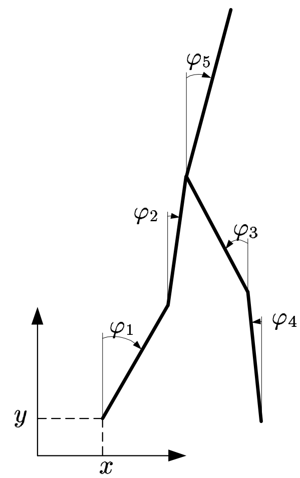

Figure 1: Configuration of a five-link bipedal walking robot.

In more advanced simulation models, the motion is not constrained to the sagittal plane, and the models most often include feet, arms, as well as additional DOF in the hip (Hirai et al. 1998 , Arakawa and Fukuda 1996 , Fujimoto and Kawamura 1998).

In general, there are two types of bipedal gaits: static walking, where the projection of the centre-of-mass of the robot is kept within the area of the supporting foot, and dynamic walking where this is not the case. Static walking is easier to implement, but is usually unacceptably slow, with individual steps taking several seconds (Cheng and Lin, 1995). In dynamic walking, posture control based on dynamic generalizations of the concept of centre-of-mass, such as the zero-moment point (ZMP) (Arakawa and Fukuda, 1996) and the foot-rotation-indicator (FRI) (Goswami, 1999) are used for generating stable bipedal gaits.

The ZMP, originally introduced by Vukobratovic and Juricic (1969) is the point on the ground where the torques around the (horizontal) x and y axes, generated by reaction forces and torques, are equal to zero. If the ZMP is contained within the convex hull of the support region defined by the feet (or foot, in the case of the single-support phase), the gait is dynamically balanced, i.e. the robot does not fall.

There are several different approaches to gait generation. Assuming that an adequate model of the environment can be generated, it is possible to generate bipedal gaits off-line, and then implement them in the robot (Hirai et al. 1998, Huang et al. 2001a). Another approach is to use an on-line controller, which generates the appropriate torques according to some control law. Fujimoto et al. (1998) used this method to generate a bipedal walking pattern for a 20-link simulated biped. The resulting controller was implemented in an actual biped with 14 degrees of freedom. Using on-line motion planning, rather than off-line trajectory generation, higher walking robustness may be achieved but at the expense of an increased demand for computational resources.

3.1 Biologically inspired computation methods in humanoid robotics

Since humanoid robots are inspired by the properties of a biological system – humans – it is not far-fetched to consider biologically inspired computation methods when generating gaits and other behaviors for humanoid robots.

Such methods, particularly genetic algorithms (GAs), have been employed by several authors. Arakawa and Fukuda (1996) used a GA to generate natural, human-like bipedal motion based on energy optimization, Wolff and Nordin (2001) implemented an evolutionary strategy to improve a hand-coded bipedal gait in a small experimental humanoid (ELVINA), shown in the left panel of Fig. 2. Pettersson et al. (2001) used a GA to develop energy-optimized bipedal gaits as well as robust balancing in the presence of external perturbations. GAs have also been used for generating robust gaits on the Aibo quadrupedal robot (Hornby et al. 2000).

Inspired by neurobiological considerations, Shan et al. (2000) used central pattern generators (CPGs), which are believed to control oscillatory processes in animals. A recurrent neural network CPG was optimized using a GA, and was shown to generate a stable bipedal walking pattern.

In general, the use of genetic (and related) algorithms in humanoid robotics seems well motivated since these methods can be implemented even in cases where a complete dynamical model of the system under study is either not available or too complex to be useful (Wolff and Nordin, 2001). Furthermore, GAs allow a large degree of flexibility in the optimization process. This property was used by Paul and Bongard (2001), who employed a GA in order to optimize both the controller and the morphology of a simulated bipedal robot.

3.2 Advanced locomotion

While the generation of stable bipedal gaits on flat ground has been at the focus of much of the research in bipedal robotics to date, some researchers have also begun to investigate more advanced types of locomotion, such as e.g. stair climbing. Honda's latest humanoid, ASIMO, is able to negotiate stairs, as shown in the right panel of Fig. 2. Furuta et al. (2001) developed a small bipedal robot, 'morph', capable of a large range of joint movements, allowing for more complex motions. Among other motor behaviors, a somersault motion was implemented in this robot.

4 Other behaviors

As bipedal robots become more advanced, the focus of research in the field is likely to shift to behaviors that are not limited simply to physically moving the robots forward. Examples of such behaviors are localization of sounds, visual tracking of objects, grasping and carrying of objects, as well as more elaborate cognitive abilities, such as the task of selecting an appropriate activity, see e.g. Brooks (1996) and Kanehiro et al. (1999).

The problem of stair detection, and indeed image processing in general, is complicated on humanoid robots because of the need to compensate for the motion of the robot. Albert et al. (2001) investigated detection of stairs using two cameras and a line laser implemented in the bipedal robot BARt-UH.

At the MIT AI lab, several studies of interactions between humans and robots have been carried out. An important aim with this kind of research is to supply robots with

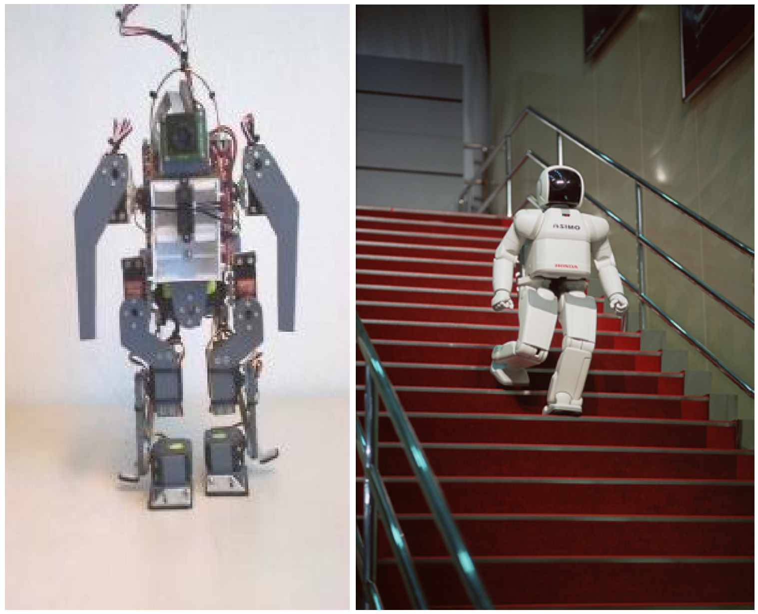

Figure 2: Left panel: The experimental autonomous humanoid Elvina developed at Chalmers University of Technology in Göteborg, Sweden. Right panel: The ASIMO robot, developed by Honda. Reproduced with permission of Honda.

the ability to interact socially with humans, for instance by interpreting the visual cues provided during e.g. a discussion (Adams et al. 2000). At Waseda University, a 28-DOF robot in the form of a human-like head, and with the capability of expressing several different emotions, has been developed in order to study interactions between humans and robots (Miwa et al. 2001).

Auditory processing, used for example when tracking a speaker, has been implemented in several robots e.g. SIG (Nakadai et al. 2001), Kismet (Breazeal, 1998), and Robita (Matsusaka et al. 1999). Nakadai et al. (2001) used a combination of visual and auditory cues in order to track a human speaker.

5 Humanoid robotics projects

As mentioned above, the number of active humanoid robotics projects is growing rapidly with time. Thus, given the limited space available here, it is impossible to list all projects, let alone describe them. However, a listing of some selected humanoid projects is shown in Table 1. The table includes both industry projects and projects carried out in academia.

6 The future: applications of humanoid robots

Once fully developed, humanoid robots and other walking machines will be useful in many different applications. Clearly, it is too early to try to list all possible applications. However, already now, several possibilities have been presented, some of which are:

Lab	Robot name	WWW	Reference
Honda	ASIMO	www.honda.co.jp/ASIMO/	–
Sony	SDR-3X	–	Kuroki et al. (2001)
Fujitsu	HOAP-1	pr.fujitsu.com/en/news/ 2001/09/10.html	–
MIT	Cog	www.ai.mit.edu/projects/ humanoid-robotics-group/ cog/cog.html	Brooks et al. (1998)
Kitano Symbiotic Systems Project	PINO	www.symbio.jst.go.jp/ ˜yamasaki	Yamasaki et al. (2000)
Waseda Univ.	iSHA	www.phys.waseda.ac.jp/shalab/ ˜kenji/iSHA/index.html	Suzuki and Hashimoto (2001)
Bundeswehr Univ. Münich	HERMES	www.unibw-muenchen.de/ hermes/index.htm	Bischoff (1997)
Chalmers Univ. of Technology	Elvis	humanoid.fy.chalmers.se/	Nordin and Nordahl (1999)
INRIA, France	BIP2000	www.inrialpes.fr/bip/ Bip-2000/index-en.html	Espiau and Sardain (2000)

Table 1: A list of selected humanoid projects.

Prosthetics Walking machines can be used as walking aids for paraplegics or limb amputees. (Acosta-Márquez and Bradley, 2000),

Inspection of dangerous environments A robot controlled by remote operation, such as e.g. the Honda ASIMO robot, could find uses in, for instance, inspections of dangerous environments.

Agricultural work As mentioned above, a walking robot does less damage to the ground than a wheeled robot, and is also able to step over obstacles and move in complicated, non-smooth terrain.

Entertainment The entertainment value of walking robots, whether humanoid (e.g. Honda's ASIMO, Sony's SDR3X) or quadrupedal (e.g. SONY's AIBO) is apparently very high, and will certainly be exploited further in the near future (Kuroki et al. 2001).

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