Biorobotics Laboratory - EPFL

Bipedal locomotion in humans, robots and avatars : a survey

PhD Seminar on Topics in Autonomous Robotics

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Abstract
After reviewing basics in neurophysiology, computer animation and humanoid robotics, we take a look at several locomotion engines, built using physical models, control theory or learning from motion-capture data. Bio-inspired robotics uses circuits based on CPG and neural oscillators. Genetic Algorithms and Neural Networks allow to evolve and learn the parameters of these models to be optimized. We then introduce more constraints, such as unknown irregular terrain, obstacles, clothes, loads and strong perturbations, to design gaits that are still stable, and natural-looking. Finally, we look at expressive movements and behavioral animation, as high-level ways to design aesthetically pleasing gaits.

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Literature review on locomotion

[key subject descriptors : autonomous agents, locomotion, biped, computer animation, robotics, artificial intelligence, artificial life, bio-inspiration]

0. Introduction

Creationists claim that the human being was created by a mysterious entity called God out of clay, before all other animals. Evolutionists think that the modern human species comes from the chimpanzee, but have not been able to trace precisely when the *Homo erectus* decided to stand on its two back legs in order to liberate its front legs to manipulate objects and become skillful in the design and use of instruments like tools, weapons and musical instruments. The comparison of DNA in various mammals can help to understand phylogenetics, which, according to Darwin, is the evolutionary process during which some species survive others. If not inherited, many skills can be learned, but this requires an advanced learning system like the brain.

Locomotion is considered to be a basic skill that any human can learn during his or her first years of age. How infants do this is still a puzzle to scientists and probably remains an act of faith which has to be encouraged by the caregivers.
In this literature survey, we focus first on how the human body manages to walk, from a physiological point of view. We consider the problem of learning movements and developing a stable cycle in order to move forward; then we look at trajectory planning and higher-level goals. In the tradition of biomimicry or bio-inspired engineering, it is common to look at nature's trickery and attempt to replicate this in artificial systems. We will look at how researchers have used this technique to create bipedal humanoid robots who can walk, dance, and run. Finally, we are interested in how these findings can be applied to the field of computer animation, in order to create more naturally-looking motions in computer-generated films and video games. Especially for productions that require the animation of hundreds or thousands of extras, locomotion engines are essential parts of today's softwares used in the entertainment industry.

0.1 Autonomy and freedom

This literature survey is done in the context of a PhD seminar called «Topics on Autonomous Robots», therefore it is important to make a connection with the topic of *autonomy*. Luc Steels gives a good definition of autonomy in [ste95] useful for understanding biological systems and robotics ; and Thalmann in [tha05] for a discussion restricted to screen-based animated agents.
For the purpose of this survey, we will restrict our view of autonomy to the ability for an agent moving in space to : - define its own trajectory; - be able to walk without the assistance of another person; - be able to recover from falls; - arrive to its destination in a finite time;
All this has to be achieved with a number of constraints, which are due foremost to physical laws and limited energy (or computational power). In this study, we are interested in the problem of walking on solid ground (as opposed to flying in air or swimming in liquids), on Earth. Our basic setup is a perfectly flat terrain with no walls (possibly of infinite dimensions), that presents enough traction in its physical microstructure that it is not slippery. More complicated environments and constraints are introduced in section 4, including ways to overcome them.
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0.2 Symbolic aspects

In human culture, the upright posture is of utmost symbolic importance. This is why the loss of one's legs is one of the most dramatic events that can happen to a person today. Modern medicine is helpless when confronted to cases of spinal injuries. In the Christian religion, Jesus Christ is supposed to have cured a paralytic man who could «walk again», in the same way that he helped a blind man to recover the sense of vision. If we manage to understand neurophysiology well enough in order to achieve these miracles, science would certainly gain the respect that it deserves, in a time of uncertainty and disbelief.
In the Jewish religion, a Rabbi from Prague is supposed to have managed to create a «Golem» - an artificial creature - but he is said to have decided to de-activate it when the robot started to go out of control. The Golem is perhaps one of the oldest mention in the Western literature of a robot, before Karel Capek introduced the term «robot» in our vocabulary. We are interested in the applications of the work of Norbert Wiener and his fellow cyberneticians to the design of control systems that can stimulate muscles or motors in order to simulate or replicate the human walking cycle. With a mix of neuro-engineering and exoskelettons, there are many technologies being developed today that can assist patients to walk again, but also augment the performances of soldiers.

In Polansky's film «Bitter Moon», a writer explains how his wife broke his legs in order to keep him under her control and make him completely dependent of her. In «Misery», a similar plot is revealed : this time, a writer is kidnapped by one of his fans who breaks his legs and forces him to write a sequel to a series of novels which he had decided to stop. In both films, we realize how someone's autonomy can be jeopardized when loosing the use of his legs. Even though in Europe architects and urban designers are making efforts to facilitate wheelchair access to public spaces, many buildings have staircases and no ramp or elevator. The creation of sports events for handicapped people is attempting to change this, and to show that it is possible in a technological society to have a enjoyable life even when suffering from some form of mental or physical anomaly. As an artist, I have been involved last year in a live performance at the Centre des Arts de Enghien-les-Bains (North of Paris), together with a celloist, a dancer and a drummer, where I had to fall on stage. In slapstick, falling can be extremely funny and humorous. However, in the case of a military march, or if it has not been planned by the performer, it can also be extremely dramatic or even humiliating. In French, the word «chute» can refer :

- to the fall of a body as described by Newton,
- to the demise of an important leader,
- to the final act of a theater play or performance, or by extension to the «deux ex machina» resolution of any form of narrative.

In this survey, we will examine how recent attention in the field has been devoted to avoiding falls due to obstacles or unknown terrains, to more stability and resilience to perturbations, but also to the emergence of algorithms that allow robots to recover from their fall, such as in the case of the NAO robot who is capable of getting back on its feet even if pushed on purpose by an operator.

In military marches or haute couture fashion shows, locomotion is key and has to be achieved in a certain way. In the former case, precision is sought, whereas in the latter, charm is the most important factor. The distinction between these two objectives will be discussed in our section on advanced topics.

0.3 Locomotion studies in art history

Finally, I would like to emphasize how the birth of cinema is closely intertwined with the desire to understand scientifically how humans and animals move. Etienne-Juley Marey in France and Edward Muybridge in California were both intrinsically motivated by this intellectual quest [ruina] when they both invented chronophotography, which became the precursor of modern cinema.

1. Background

In this background section, we will make a review of basic definitions and concepts that are necessary to define our subject matter.

1.1 Physiology

In order to synthesize locomotion systems, the bio-inspired approach consists in studying how nature has solved this problem. The most ancient book we have on the subject is *De Motu Animalium* (On the Movement of Animals) by Aristotle. More recently, the sciences of *neurophysiology* and *kinesiology*. Nikolai Bernstein (1896-1966) is a pioneer in these fields, and he has used cyclographic techniques to study human movement. He introduced ideas in the field of *motor control* and *motor learning*, and coined the term *biomechanics*. For a long time his writings were only available in Russian, and Mark Latash has explained his work in English. In [neurophysiological basis of movement], Latash describes neural cells in the brain, the spine and in the nervous system, explaining voluntary and involuntary (reflex) muscle movements [yan90,zeh99]. An entire chapter is dedicated to locomotion, where the notion of central generation of motor schemas is introduced. In mammals, a controversy remains as to the part of locomotion which is controlled from the brain, from the signals that are automatically generated by the spine. Some reflexes apparently do not need to query the brain in order to be executed, including the ability to keep balance and to avoid obstacles. A network of neural cells in the spine is able to generate oscillatory electrical (inside a neural cell) and chemical (in the synapse) signals which can be transformed into a rhythmic muscular activity such as locomotion. These specialized neural circuits are referred to as «*neural oscillators*» or «*central pattern generators*» (CPGs).
The modelling of these signals with artificial neural networks is due to the work of Norbert Wiener and his colleagues who created the field of cybernetics, based on control theory with open and closed loops (feedback). Some cells are inhibited, and others are stimulated in the Central Nervous System, based on sensory inputs (haptics and proprioception). Proofs of this have been obtained by spinalizing animals (such as rats or cats) and showing that they are still capable of walking [shi76, mac02]. This embodied approach to AI interested in modeling and replicating the body and its movements rather than the mind and its abstract thoughts was pushed forward by Rodney Brooks [br085] and is discussed in section 3.4. The modelling of neural oscillators is discussed in section 2.1.
Nicolas Rashevsky [on the locomotion of mammals] has contributed a lot to the mathematization of biology and contributed to a definition of life. His PhD student Robert Rosen [Anticipatory Systems] was a theoretical biologist, investigating complex systems and life, anticipating the work of Christopher Langton in Artificial Life (AL) [lan95]. Some researchers have taken the approach, in cognitive development, to study how infants learn how to walk [hae00].

Whereas anatomy is the study of the physiological constitution of humans and animals, kinesiology is a branch of biology interested in describing the movements that animals can perform, when involved in certain types of actions, such as walking, running, hopping, jumping, swimming, flying, etc. In humans, the description of locomotion is very sophisticated, and depends on the natural language used. In French, expressions such as “gambader”, “sautiller”, “traîner du pied”, “courir”, “sauter à cloche-pied”, “tenir en équilibre sur un pied” describe certain attitudes and types of walks or gaits. In horses, the pace is used to distinguish between «walk», «trot», «canter/lope», or «gallop». In man, the most basic distinction is between walking and running, and its transition has been extensively studied.

The musculoskeletal system (also known as the locomotor system) is an organ system that gives animals (including humans) the ability to move using the muscular and skeletal systems. The musculoskeletal system provides *form*, *support*, *stability* and *movement* to the body [tag95a,tag95b].
In man, the locomotion system is composed of the 3 lower limb segments : the *femur* (thigh), the *tibia* (shank) and the *foot*. The relevant muscles that are directly responsible for moving these limbs are essentially (on each leg) : *rectus femoris* (RF), *vastus lateralis* (VL), *biceps femoris* (BF), *tibialis anterior* (TA), *gastrocnemius lateral* (GL), *soleus* (SOL). The activity of these muscles can be monitored non-invasivally with electromyography (EMG) [bas85] ; A mapping of these electrical signals to segment angles has been presented by Cheron et al. using recurrent neural networks (RNN) in [che03b]. The leg is connected to the trunk at the hip (pelvis). The six major determinants of human gait are : pelvic rotation and tilt, knee flexion, hip flexion, knee and ankle interaction and lateral pelvic displacement [bas85]. [fig ?]
Depending on their function, muscles are called *flexors* or *extensors*, *abductors* or *adductors*, *pronators* or *supinators*, *rotators* or finally *circular* (sphincter).

The sensorimotor system [rie02] depends on sensory integration which is the neurological process that organizes sensation from one’s own body and the environment; the brain and the nervous system generate usable functional outputs based on these inputs. In robotics, inputs are acquired from sensors, processed by a central computational unit or distributed computational units, and outputs drive motors to generate an action on the environment. The robot/computer model is used to understand how the body works.

Human walk is a cycle whereby the center of gravity is moved from left to right, from right to left, and so forth. As one foot is on the ground (*stance* phase), the other foot is in the air (*swing* phase). In walking, there is a short time during which both feet are on the ground at the same time (*double support* phase). In running, there is no double support phase, which means that the runner hops on one leg and then on the other as far as possible. The phase during which neither foot touches the ground is called the *flight* state, as opposed to the *support* state. Running is quite unstable and relies on fighting gravity by pushing against the ground. A particular field of study is the *walk-run transition*. In terms of foot anatomy and point of contact, the *heel* is used to land the body, whereas the *toes* are used to lift the body up and away. A temporal representation of gait consists in representing which foot is touching the ground, on a timeline. A spatial representation of gait consists in representing foot placement spatially on the ground, including the orientation of the foot. [fig ?]

Choreography is the art of creating and writing down dances, using dance notations. Dance notations are very precise about the placement of the feet, whether it's a waltz, tango, cha-cha-cha, box step, etc. But they also include body posture, hand movements, head position, etc. The most common dance notations are Laban and Banesh. Some softwares such as Life Forms by Credo Interactive have been designed to do this on a computer. For making dance scores, there exists LabanWriter and LabanReader. Another option is to use dance ontologies [el raheb, saad]. In classical dance, many of these terms are present in the vocabulary and simply described using natural language, such as *grand écart* (split), *développé*, *grand plié*, *salto*, *entrechats,* etc.

1.2 Animation

Animation (or «moving pictures») is the art of visually recording movement and playing it back. It finds its origin in so-called pre-cinematic devices such as the *zoopraxiscope*, predecessor of the *kinetoscope*. A series of images are drawn onto a disk, and the disk is spinned quickly : after a certain rate called the *flicker fusion* rate, the retinal persistence of vision gives to the viewer the illusion that the image is moving. With the advent of chemical processes to fix an optical image onto a substrate, film was born; although today video is used and CCD sensors are replacing celluloid. In my paper «From Absolute Cinema to the Film of the Future» [lew08], I distinguish between 3 methods co-existing today to create moving images : the hand, the camera and the code. The *hand* consists in drawing (by hand) analogically or digitally a scene, using conventional drawing or painting substrates such as paper or canvas, or a computer with Adobe Photoshop, Illustrator, Flash and a Wacom tablet. Scenes are drawn frame by frame, but certain elements can be conserved from a frame to the next. Usually, animators will draw keyframes, and the computer will interpolate to generate in-between frames (tweening). The *camera* consists in recording automatically the real world, by sampling and digitizing the values measured by sensors (usually optical, but not always). The *code* consists in devising algorithms based on physical models or control theory to generate images. Usually these 3 methods of image-making are used together. Modelling techniques in 2D or 3D are based on scanning an image or a real sculptural model, or by virtually sculpting directly with a CAD tool such as Maya, 3D studio max, Houdini, Softimage, Blender, etc. *Rotoscoping* is the technique by which the animator draws on top of a filmed image, by keeping only its contours (a very ancient technique used by architects with the *camera lucida*). Walt Disney is famous for discouraging his animators to use this technique in their work, because he considered it «cheating» and photorealism was not what he was looking for. More recently, Bob Sabiston (a student of John Maeda) has invented a rotoscoping tool used for films with Linklater on «Waking Life» or «A Scanner Darkly».

Computer-generated animation started to emerge when GPUs and CPUs were fast enough to render complex scenes in 3D, by pioneers such as John Whitney. Daniel and Nadia Thalmann were among the first scientists to reproduce the human figure in a computer [tha82] ; their avatars of Marilyn Monroe and Humphrey Bogart became icons of the computer graphic industry, represented by the ACM SIGGRAPH conference held annually. In 1970, Masahiro Mori published a paper called «The Uncanny Valley» where he described the problem of excessive realism in robots and synthetic humans, which can be experienced in movies such as «Final Fantasy» or «Polar Express». In terms of feature-length animated films, «Le roi et l'oiseau», «Toy Story», and «Shrek» are considered milestones ; the first one because it's 100% French and the dialogs were written by a poet, the second because it is entirely computer-generated and the third because all characters are based on motion capture.

For walking motion synthesis [bou90, bou04], the Humanoid Animation Working Group has proposed in the H-ANIM standard a model of the human body. The problem of inverse kinematics (IK) [bae02] consists in finding the most appropriate way to move a redundant articulated structure in order to reach a certain point of space with its extremity. A common problem in animation is occlusion : when rendering a scene from a particular camera viewpoint, some objects will be partially hidden by others. The rendering engine needs to compute the position of each object relative to the camera. For locomotion, this becomes an issue when walking because during the support phase, the foot needs to be touching the ground [gir85] - these animation artifacts are common especially in video games. One strategy could be to cover the feet with some grass. The advantage of animation is that, whether interactive or linear, it can constrain the camera angle and movements to only present things under their best light and best angle ; for camera control, see [dru92]. It remains the case that, if using manual animation (the hand) and not pre-recorded motion, the computer will need to interpolate between keyframes - for human figures we talk about *key poses*.

Bruderlin is an expert of animated human locomotion per se. After his Master's on the subject [bru84], he published in Siggraph in 1989 [bru89]. In [bru96], a paper dedicated to running figures, he uses the terms «*knowledge-based*» or «*knowledge-driven*» to designate this type of animation. This "knowledge" is an arsenal of tricks of the trade accumulated over the years by computer animators, and incorporated into algorithms and engines used in animation software. Commercial software for image synthesis include : Maya, 3D Studio Max, RenderMan, Alias Wavefront, SGI, Silicon Graphics, Blender, AutoDesk. Specific to walking : Poser (Pro), MotionBuilder, Boston Dynamics - BDI Guy, Credo Interactive - Life Forms Studio, 3D Studio max - Character studio, Softimage - RTK. In video games, locomotion engines are starting to appear also : see for example Unity's locomotion engine [joh09].

A good overview of computer animation techniques is given in [mul99] and some of the most recent papers on the problem of locomotion are [cor11] for quadrupeds and [cor10] for bipeds ; they both show that the field is still young.

1.3 Robotics

The field of robotics is dedicated to the problem of building machines that can move in the real world. Since the publication of Rodney Brooks' paper «Elephants can't play chess», a large proportion of the international Artificial Intelligence community has decided to walk away from purely abstract problems that had occupied scientists for years, in order to concentrate on the extraordinarily difficult problems that simple animals, ranging from micro-organisms to elephants or dinosaurs, have to cope with in their everyday life in order to survive. The International Society of Adaptive Behavior, holding the SAB conference every two years, presents some of the most original contributions in the field.

As a metaphor with humans and animals (from animals to animats), we distinguish in robots :
1. the purely passive mechanical structure of the robot (its skeleton, bones and articulations) - links and joints
2. the muscles [cellules du muscle] - actuators (usually called motors)
3. the skin [epithelial cells], senses and peripheral nervous system - sensors
4. the brain and central nervous system [neural and glial cells] - processors

In robotic terms, the DOF (degrees of freedom) problem consists in describing the human body as made up of rigid links connected by joints. Each joint usually has up to 3 DOFs. In human locomotion, the hip joint is the most problematic [aoi2007] ; it is seen as describing an 8 shape during the walking cycle. The first question when building a robot is, to define its number of DOFs, which goes together with its morphology, and will allow to build its main physical structure (its skeleton).
After that, the most common method to describe movement is to take the skeleton of the animal and to describe its movement by using a joint vector, which is a vector that contains the angle of each joint. If a joint has more than one degree of freedom, then multiple angles will describe the state of that joint. We say that this vector describes the state of the robot in *joint space*. Going from a joint description to computing the torques is a complicated problem [aoi07].

Vukobratovic was the first roboticist to study extensively the problem of gait and locomotion in biped humanoid robots. He introduced in the 1970s the idea of the ZMP (Zero-Moment-Point) which is a sort of Centre of Pressure (CoP) that can be calculated given the geometry of the robot while it is moving - and it was implemented for the first time in 1984 in Japan on the WABOT WL-10RD robot. The vertical projection of the robot's ZMP onto the ground has to be located within the convex hull created by the support legs of the robot in order to be stable, or to use the right terminology «*dynamically balanced*» [vuk04]. *Static balance* is the simple case where the robot is standing but not moving - quasi-static would mean that the robot is moving sufficiently slowly that it can be analyzed only using statics. There seem to be disagreements and variations among the robotics community in the way that the notion of ZMP is precisely defined. Gaswami has introduced the notion of Foot-Rotation Indicator (FRI) in his analysis of why robots fall [gos99].

Here is a list of the most famous walking robots built recently, with references to papers that use them as testing platforms or that explain how they were designed (hardware or software) :
Honda : Asimo (first humanoid robot that can walk : P3) [hir98]
Sony QRIO
Fujitsu Hoap I, II, III [mor08] [sha02]
Aldabaran NAO H-25
BIP [aze06]
RABBIT [aze06]
RunBot [gen05]

HRP-2 [kaj03] HRP-4
WillowGarage PR2
HUBO-2
MAHRU III

2. Locomotion engines

After defining some introductory notions in physiology, computer-based animation and robotics, the aim of this section is to now solve our main problem, which is to create models and algorithms that will allow us to reproduce human locomotion. To quote Raibert : “One might expect the various workers involved in the study of control algorithms for legged locomotion animators, robot engineers, and biological scientists to differ in their criteria for successful algorithms. Such criteria could include precision of control, generality of control algorithms with respect to diverse behaviors and diverse creatures, the aesthetic appearance of the resulting movement, the simplicity and elegance of the solution, or the degree to which an algorithm explains the workings of animals.” [rai91] Raibert emphasizes how the study of animals can lead to the design of better robots, which in turn can be applied to the field of computer animation and visualization. But it’s also true that cyberneticians and robot designers can learn a lot from computer graphics - and it’s also the case that before using expensive hardware, most engineers start by running numerical simulations on a computer screen.
The nature of the final application will guide the locomotion designer to choose amongst the various methods at hand.
In the following subsections, we present approaches based on CPG (or *neural oscillators*) (§2.1), on physical models (§2.2), on control theory (§2.3), and finally on motion capture (§2.4).
Methods described in 2.1, 2.2 and 2.3 are more elegant and simple solutions, which could be called *procedural*. Whereas methods described in 2.4 are based on large amounts of data resulting from the measurements of real motions and could be called *statistical*.

2.1 Oscillators

The first approach, also used by simple 2D web-based apps such as PuppetTool [w6] or SodaPlay [w7], but also Animata [w8], is to drive the motors that will move the skeleton’s limbs (the joint angles), by using simple signal generators based on the sine wave. A simple sine wave is characterized by its amplitude A and its phase ϕ.
Morimoto has shown in [mor06] how it is possible to create such walking signals by the modulation of simple sinusoidal patterns. The idea is to use *coupled oscillators*, so that one leg swings forward while the other is used as a support, etc. The paper explains what should be the frequencies of and phase differences between the various oscillators driving the robot (here 4) so that the robot can start walking. There are various parameters that can be tuned to adjust the gait. The authors first tests their models on a simulator, and then on two different robots in the physical world.

Based on the neurophysiological study of vertebrates, another bio-inspired method consists in trying to imitate the signals generated by the spinal cord of these animals ; for that reason, these oscillators are often called *neural oscillators*. In [miy98], Miyakoshi explains how he built a neural oscillator system for generating biped motion, but only in a simulator ; the basic unit of this simple neural circuit is a pair of two neurons (flexor and extensor) that can excite or inhibit each other, and by playing on their time constants, it is possible to generate oscillatory signals. Miyakoshi uses a total of 3 oscillators, one for hip motions, and one for each leg. Dutch biophysicist Duysens gives lessons in [duy02] from his study of man and cat to improve such a bio-inspired design. The most comprehensive model of the neuro-musculo-skeletal system for human locomotion is given by Taga [tag95a,tag95b].

When the network of neurons controlling the so-called motoneurones (directly connected to muscle fibers) become complex, it is common to refer to these circuits as central pattern generators (CPG). Such networks generate the rhythm and form the pattern of the locomotor bursts of motoneurons. A comprehensive survey of CPG in humans, animals and robots can be found in [ijs08]. Righetti has applied these methodologies, using adaptive Hopf oscillators, to generate online trajectories for a simulated Hoap-2 robot (in Webots), in a supervised learning framework [rig06].
In 2005, Komatsu proposed the so-called Hybrid-CPG (H-CPG) that takes into account ground floor reaction force (both horizontal and vertical) for each foot ; their ‘KAAL’ robot manages to walk and run on a treadmill.

If we approach this problem from the perspective of a non-linear dynamic system, we can, as Aoi does in [aoi05] consider steady walking in biped robots as implying «a stable limit cycle in the state space of the robot». Aoi takes into account the movement of the arms, and uses the foot sensors (touch sensor signal) as inputs to generate a stable cycle. He also introduces an «Inter-Oscillator» which controls the arm movements based on the leg movements. The robot used in this study is the Fujitsu HOAP-1, which manages to walk on a flat floor, but also upslope and downslope.

Energy can be minimized if the driving signals take into account the geometry of the robot, and in particular its resonance frequency. Ahlborn (physicist) and Blake (zoologist) explain how to compute this [ahl02]. This frequency depends on g (gravitation) and the length of the legs L. The authors describe how to compute the walk-run transition (Froude’s number). All animals maintain resonance during running. There is also a discussion about elastic vibrations and leg stiffness, which could be corrected by having the right running shoes (for humans) but typically modeled by the «leg spring» in robot and virtual models.

Recently, the team of Bernard Espiau at INRIA has taken the approach of *sensor fusion*, imagining a general method to map sensor inputs (such as accelerometers, gyroscopes, position or touch sensors) to motoneuron outputs [hel08]. They use Van der Pol oscillators and Hopf oscillators.

2.2 Physics-based

«Physical constraints shape the dynamics of the interaction of the embodied system with its environment - for example, because of the way it is attached to the body at the hip joint, during walking a leg behaves to some extent like a pendulum - and can be exploited to achieve stability, maneuverability, and energy efficiency» [pfe07]
For more papers on the *inverted pendulum* model, see [sri06] and [sug02].

Passive dynamic walking (PDW) robots are robots that simply use gravity and the pendulum effect in order to move forward. They can be built mechanically with no active motor whatsoever, and manage this way to move forward on a inclined plane. The expert of this idea is Tad McGeer who wrote the classic paper «Passive Walking with knees» where he explains how such a robot can be built with knees, in order to be more stable. Such a robot is called *planar* because it only moves in one plane (it never turns).

Virtual Model Control is a design methodology introduced by Jerry Pratt from the MIT Leg Lab ; in [pra01], he proposed virtual model implementations for bipeds. The idea is to attach virtual masses, springs and dampers (even virtual motors) to the robot, and from this model, to generate the desired joint torques. The result will create the illusion that these virtual elements are present.

Physicist Popovic who studied with Vukobratovic and applied his theory to the construction of a robotic leg for Hugh Herr who lost his leg while mountaing-climbing, have showed that there is *conservation of angular momentum* during human locomotion [gos04] [pop04]. In addition to being an elegant model of human walking, this principle can be applied to design robust locomotion in bipedal robots.
The notions of linear and angular momentum is also used by Kajita et al [kaj03] to plan specific motions such as walking, balancing, and more.

2.3 Control theory

Control theory can be defined as the art of how to design a stabilizing feedback system, also called closed-loop, which is widely used in industrial applications for its precision. The basic idea is to iteratively minimize the error between the measured position of an effector, and the position which the animal or robot wants to reach. Mathematical tools are the z-transform (to model delay), integrators, differentiators (PID controller). The mathematical theory is elegant and includes the use of the Z-transform or Laplace transform, to visualize where the poles of the transfer function reside - this allows to determine whether the dynamical system will be stable or not.

RABBIT is a bipedal robot with no feet [w3]. It was created in Grenoble to as an experimental platform for the study of walking, and is based on advanced control theory. Its design is described in [che03]. The absence of feet makes the ZMP criterion not applicable.
In terms of stability analysis, the recent PhD thesis of Wieber [wie00] is excellent, and summarized in [wie02]. He compares the ZMP approach with Lyapunov [lya92] stability criteria. Basically, the problem of stability for a walking humanoid is simply to manage to avoid falling. Wieber looks at perturbations in the state space, and introduces the notion of the *viability kernel*, which can predict which kinds of perturbations are reversible and can be compensated, vs. those that irremediably will lead to a fall.

Henri Poincaré, French physicist and mathematician, precursor of the theory of relativity, introduced the notion of *strange attractor* in chaos theory, non-linear dynamics and control theory. Grizzle has applied his method to the class of biped models in [gri01]. Extending on this idea, Chevallereau introduces the idea of hybrid zero dynamics (HZD) in [che04]

2.4 Motion capture

Motion capture consists in recording the movement of real animals, so that it can be mapped to a robot or an avatar.
The most common method to do this is called today *motion capture*.
Recently, the Kinect introduced by Microsoft has caused a stir in the R&D world, because this small device manages to extract in real-time pose information from multiple human subjects, without using markers, but relying only on *computer vision* techniques [sho11]. It usually runs at 200 frames per second.
A more common technique, used by professionals, consists in placing reflective markers on the subject, at key points (such as joints). Each marker becomes a dot, and the computer will discard all other information but the displacement of these dots

in space and time, possibly by using multiple cameras filming simultaneously, in order to allow for partial occlusion of a body part by another, and to recover full 3D information [men11].
In any case, it will be necessary to go from one representation to another (from dot movements to variations of joint angles).

Various methods have been devised to remap this motion capture data : for example to adapt the same motion to another skeleton with a different anatomy (re-targetting) or to change the speed of certain parts of the movement (time-warping). Another problem is to interpolate, i.e. to generate intermediate positions which were not recorded, but which can be inferred from the data. Finally, extrapolation is the ability of an algorithm to generate completely new sequences of movements, by learning from the data, and reproducing it with different parameters or initial conditions, or different constraints. More generally, *motion editing* is the process by which a recorded motion will be edited so that it can be usable. The processing of these signals is described by Bruderlin in [bru95]. Motion blending is the combination of two separately recorded motions into one new signal representing both [par02].

These methods are mostly used for computer animation, and omnipresent in the film and video game industry, but they can be applied also to robots, see for example [cho02] or [nak03].

Professional motion capture / motion tracking systems with markers and multiple cameras include the Vicon system (optical) or Flock of Birds (magnetic). The industry also talks about *Performance Capture* or *Universal Capture*.
Another system, mostly used for electronic arts and dance performance, is the Kroonde.

3. Learning, evolution, adaptation

«The only process currently known to have produced an ecosystem of living creatures, and in particular, of intelligent beings, is that of natural evolution» [sip97]. In order for an intelligent fully-grown and responsible adult to exist today on this planet, 3 main processes are necessary : phylogeny, ontogeny and epigenesis. Phylogeny is the history of the species ; this long chain of mutations that have happened over millions of years, since the emergence of life on earth, to lead to the modern man, in the process of natural selection as described by Darwin. Ontogeny is the development of a single individual, since its conception in the mother's womb, including birth and ageing, as specified in the DNA. Finally, epigenesis is the process by which individuals learn, change and adapt during their lifetime (arguably modifying their own DNA in this process). We are interested to replicate these phenomena in the design of our algorithms.

3.1 Phylogeny

John Holland introduced the idea of Genetic Algorithms (GA) [hol75] in order to simulate the process of natural selection in a computer for the design of optimal controllers. When designing a system that has a very large numbers of free parameters, it is not always possible to try each combination. By encoding the design parameters of a system under the form of a string of DNA, and by making changes to that DNA (mutations), a new organism will be said to have evolved, as long as it survives the fitness function. This function evaluates the performance of the offspring according to certain criteria : the worst performers are killed, and the best are said to have survived. By repeating this process over and over, this theory says that we will always be left with the best performers.

This idea has been used in computer animation, where creatures of various generations can be seen struggling to survive with varying degrees of success. Karl Sims, for example, is famous for his work on Evolving virtual creatures [sim94] where he pioneered this concept. Still at the MIT Media Lab, Ventrella and Elliott [ven95] created a project called «Disney meets Darwin» where bipedal creatures are evolved to generate funny walks, some that are functional and other not.
In Europe, Komosinski and Ulatowski have created a software for 3D simulation and evolution, called Framsticks, where creatures can be evolved over multiple generations.

The idea is also used in robotics :
In [dip09], authors use a GA to optimize neural oscillators generating natural walking patterns.
In [rus07|, authors use a GA to find the best parameters of a neural CPG network.
The design of a GA consists mainly in choosing the parameters that will be encoded in the genome, and deciding on the appropriate fitness criteria.

3.2 Ontogeny

When a baby is born, it knows almost nothing of this world. The morphology of the baby and the hereditary traits it has inherited from its parents will express themselves more and more as the child develops and matures. In simple animals, knowledge is encoded under the form of instincts : by definition it means that an animal can know how to hunt or make a nest without needing to learn it from its parents or its peers. But all animals are equipped with a very sophisticated network of cells that exhibit plasticity, and which can remember things. For example, the immune system can learn to recognize a micro-organism in order to destroy it if it attempts to invade the organism. In our case, we are interested in the neural system which allows animals to learn new skills and become better in doing certain things when repeating them over and over.

Examples of the use of reinforcement learning in biped robots can be found in [hit06] [mat06] [mor04].

3.3 Imitation

This method of machine learning which draws a lot from statistical physics has been used, for example, to reduce the dimensionality of large datasets such as motion capture data [gla04,gla04b].

In robotics, *Learning from demonstration* or *Programming by demonstration* are new paradigms whereby the robot operator does not need to explicitly program the robot using computer code, but can actually simply show the robot what to do, either by moving the limbs of the robot manually, or by standing in front of a camera and showing what to do with gestures. Nakanishi and al. have tried this method which is discussed in [nak04]. Imitation learning as a new paradigm is described extensively in [sch99].

3.4 Subsumption

We include here a mention to Rodney Brooks and the famous subsumption architecture described in [bro85]. He applies this architecture to a walking robot in [bro89].

4. More constraints

Until now, we have studied the locomotion of agents on flat even terrains with no known boundaries. But the reality is different : rooms have walls, gardens have fences, countries have natural and man-made borders. Furthermore, the world is often populated with other agents who can be benevolent or malevolent. In this section, we will look at ways in which our robot or avatar can overcome all these obstacles in order to keep moving forward.

4.1 Irregular Terrain and Obstacles

The first consideration regarding the ground on which the agent walks is whether it is known or not. If it is completely unknown (a «*terra incognita*»), the agent typically should be extremely scared, or at least very brave. Most of the time, a supervisor will be accompanying the learning agent, but also the agent will already be adapted to the environment and will be equipped with an entire apparatus of pre-recorded reactions in order to anticipate how to react to changes or irregularities in the outside world. The agent captures new information about the world with its sensors, or by communicating with other agents, or by accessing structured news sources that have been compiled by its peers. In the context of this survey, we are restricting our enquiry to the problem of sensing the environment with vision, hearing, touch - what we call the senses in the human being. In robots, this design problem is restricted to the availability of electronic sensors in the market that can transform a measurable physical observable into an electric tension or current. In avatars, by definition any system value could be given to the agent at any given time (the problem related to God and man's freedom as guaranteed by the impossibility to know everything - Laplace's demon) ; but in order to make agents more realistic and natural-looking, animators using AI have imagined to recreate the point of view of each character, in order to detect collisions, to see and hear the world with the eyes and ears of the avatar in the virtual word. For industrial applications, we want the environment to be as controlled as possible, and thus a robot could have a full map of a plant.
Sensors are said to be *proprioceptive* if they return values related to the position of the agent and its limbs; *exteroceptive* if they return values related to external events; *interoceptive* if they return values related to the internal state of the agent (such as hunger, tiredness, malfunction, etc.).

In terms of exteroceptive sensors, most robots are equipped with foot sensors, usually 4 force-sensitive resistors (FSR) placed on each sole. These sensors will return a value whenever the foot is in contact with the floor, and that value is proportional with the ground-reaction force (how much the ground is pushing against the foot) measured in Newtons. Because of their configuration, it is also possible to know whether the foot is flat (in that case all 4 sensors should have the exact same value) or whether the foot is slighty in rotation, which can be a stability problem. Some of the control algorithms we have reviewed earlier use these sensors already, for example the phase reset algorithm [aoi06].
In terms of proprioception, some robots will be equipped with rotary shaft encoders which can measure the speed of rotation of an axle (same sensor as used in a mouse) therefore capable to sense whether the action command has been followed by an actual movement (problem of ghost limb sensations in amputees). Servos by definition already implement this feature. This could be a way for the robot to realize that it's stuck or blocked against an obstacle. Other sensors are sonars or infra-red sensors which can measure the distance from an obstacle.
Vision sensors are sophisticated sensors that measure the reflection of light - they can be 0D (one pixel), 1D (linear sensor), 2D (one eye) or 3D (two eyes). Patla has studied extensively the impact and use of vision on locomotion in humans (see for example [pat97]). Lewis has applied these ideas to robotics [lew05]. Without having a map of the terrain (which requires to trust the mapmakers, to find a map at the right scale and which is up-to-date, to locate oneself on the map - and in many cases there simply exists no map), the robot can navigate and find an optimal trajectory in space to go where is needed. Lewis discusses the problem of foot placement on a slippery or icy terrain, which is a problem where the agent would need anticipate dangers before they happen in order to avoid them.
Kim looks at the problem of slippery surfaces, and how to adapt gait accordingly [kim07], using learning and evolution.

4.2 Wearing clothes

The movement might be constrained by the clothes that the actor is wearing.
With a large dress, a woman will walk slowly ; if she is wearing heels or tennis shoes, her gait will be different. If a woman has a dress, she will be playing with the visibility of her legs and perhaps even of her underwear, in order to charm and seduce members of the opposite sex. By showing and hiding, it is possible to generate excitement and the desire to see more. The influence of dress and accessories on gait, has been studied by Nadia Thalmann, specifically within the context of rendering clothes, garments and textiles [cor02].

4.3 Carrying objects

The problem of carrying objects (which is a strategy used by some animals too) is commonly found in humans.

Any load or bag that the robot, human or avatar will be carrying, will modify the dynamic balance, and have an effect on the gait, and the overall posture. Coros examines the problem of pushing and pulling objects, or lifting heavy objects, in [cor10].

5. Advanced topics

5.1 Expressive and special gaits

It is often said that a person can be recognized by his movements - it is part of his/her personality.
A possible application would be to recognize individuals by their gait (gait recognition/identification) by using a method such as PCA. The sensitivity that humans have to small variations in human movements has been analyzed by Gunnar Johansson in this classic paper [joh73].

Kinesiologists Streepey and Gross [stre98] have analyzed the emotional content of human movement, in the context of an expressive artform such as dance. The idea would be to manage to detect between a happy walk, a sad walk, a proud walk, a loser's walk, etc, for analysis. For synthesis, these would be parameters that could be used to color the gait with a certain emotion.

Pathologic gaits [kom05] and disordered locomotion [win89] are interesting because they might be used for medical applications, in order to detect an injury or disease from someone's movements. They can be studied in order to create animated characters that are wounded or abnormal.

Jumping and hopping is studied in [ber99].

5.2 Motion planning

A lot of the robots that we have seen so far are planar. For robots that can actually turn, Aoi provided an analysis of this problem, namely how to adapt gait in order to turn, in [aoi07]. Path planning with computer vision is a classical problem of AI.

Regarding improvisation of new locomotion sequences, a creative approach would be to look at the work done in musical improvisation that can emerge in group performances [can11].

5.3 Resistance and recovery

Resistance to perturbation is key in real robots, because they involve in a physical world which is not perfect - the terrain can be slippery, there can be wind or the robot could be hit by an object. Most of the design approaches we have seen so far include a discussion of stability and control which is included in the motion algorithms, based on sensor input. The most basic protection against perturbations is called «reflex» in animals and is a low-level mechanism for reacting very fast to sudden and unpredicted changes.

To learn how not to fall : [gos99]
To learn how to resist perturbations : [abd05]
To learn how to animate reactive motions - in reaction to large external forces while still maintaining balance : [kom04]

5.4 Behavioral animation

The term of behavioral animation was introduced by Craig Reynolds (now a faithful employee of Sony Computer Entertainment America since 1998). He did his Master's at the Architecture Machine group (now MIT Media Lab) where he created one of the first example of computer animation recorded to HDTV format, together with Rebecca Allen, on the music of Peter Gabriel [w10]. This idea was revived in 2011 as part of the Google Chrome Experiments [w11] for the «Rome» music album with singer/songwriter Norah Jones, where users can explore a virtual world in their browser populated by abstract virtual creatures.

The idea of directing synthetic actors is the subject of Monzani's PhD thesis in Daniel Thalmann's lab on behavioral animation [mon04], where high-level directions are given to the virtual characters who are controlled by software agents. These agents have internal representations such as the Belief-Desire-Intention (BDI) model which allow them to prioritize tasks and have knowledge on how to perform each task, and to execute a task by dividing it into a sequence of smaller movements who are then executed by the low-level control system. In this report, we are interested in the so-called low-level control system. Blumberg et al. have designed brain architectures to generate animations of dogs and wolves, very succesfully [blu95]. For simulating crowds, the following software is used : Massive (http://www.massivesoftware.com/).

Although not specifically designed for humans but for an ecology of fishes, the PhD thesis of Tu [Tu96] won an ACM award and is very promising for how we could use these techniques with virtual humans.

Perlin (famous for the *Perlin noise*) has described the Improv system and coined the expression «Improvisational Animation» [per96] ; alas it has not yielded so far the results that it promised. Cavazza and Davenport have shown how to design Intelligent Virtual Environments and Interactive Storytelling systems where the control of characters is guided by very high-level narratives that take into account not only the past of the characters but also their personality, the history of their family, their cultural backgrounds, etc. Some of these ideas have been incorporated into the game by Maxis «The Sims» by Will Wright. A big problem is how to model emotions and feelings in humans [gra04], implemented in simulated environments for military and humanitary missions in the Middle East using voice recognition. Bill Tomlinson [tom02] tackled in his PhD the simpler problem of simulating social relationships between agents - he applied his algorithms to a pack of virtual wolves in the interactive installation «AlphaWolf».
These systems currently represent the most advanced platforms for simulating humans, as represented mainly by the efforts of the video game industry.

6. Conclusion

Biped locomotion is considered a major advance in the evolution of mammals. Its understanding can lead to the design of robots which can co-exist with humans in a constructive way. Whether it is for medical, military or entertainment applications, we have surveyed how kinesiologists study movement with physical models, based on dynamics and kinetics, but also control theory. With the study of neurophysiology, we are gaining more insights into the electro-chemical signals that control the animal muscles, and we can start to reproduce them electronically with neural oscillators and neural circuits. Taking this approach also allows to make these circuits learn and adapt to new situations. The problem of resisting perturbation and adapting to new territories is key in designing stable gaits. Many of these strategies have been reviewed, based on sensors or vision, coupled with stability analysis. Once the basics have been overcome, the gait designer can focus on editing and adapting recorded movements, but robotics and computer animation have very different constraints in what can be achieved.

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