Chapter 2

# BACKGROUND

What differentiate CMS methods are ideas of motor control. Many current CMS research studies adopted the control hierarchy of artificial systems. For these methods, no matter whether it is based on tracking or optimization, there is a clear separation of planning and execution in motor control. Body are treated as mechanical apparatus, which execute the motor commands from the neural system.

The separation of planning and execution does not exist in Motor Invariant Theory (MoIT).

Moit is based on the integrative theory of motor control [Dickinsonet al., 2000]: For biological systems, planning and execution cannot be separated clearly. Neural system plays a limited role in the planning. Body and environment are taken into consideration and motor control can only be understood from a broader perspective.

In this chapter, limitations of current CMS methods are discussed first, which are the motivation of this research. New theory is developed because these limitations cannot be overcome without breaking the already theoretical framework. Supporting biological research studies are discussed later, which serve as justifications for MoIT.

## 2.1 A survey of CMS

Many methods have been developed in CMS, making it impossible to include all the work in this chapter. For a short discussion, CMS methods are categorized by their principal control models: memory based or computation based. Memory based control model is foundation of the many data-driven techniques; most procedure methods are computation based. Pros and cons are discussed in categories.

## 2.1.1 Data Driven

Data-driven methods are based on ready motion data, generated by Key-frame or Motion Capture(Mocap). In practice, motion data are segmented into short time clips. An animation is synthesized by selecting motion clips and connecting them together[Kovar and Gleicher, 2003; Parent, 2002].

Like other example based methods, data driven methods can generate good results if similar motion clips are available, but difficult to generate adaptation or novel motions, either for a different character or scenario. This “re-targeting” problem is a big challenge for CMS research.

In practise, the versatility of motion requires a large database. As a consequence, data management becomes another problem. The Annotation Database [Arikan et al., 2003] and the Motion Graph [Kovar et al., 2008] are proposed. Currently, catalogue and search of motion data are not trivial and remain open[Keogh et al., 2004; M ̈ ller et al., 2005].

### 2.1.2 Procedural Method

For physics based CMS, different procedural approaches have been proposed.

• Tracking Controllers

Some early research applied classical PD controller [Raibert and Hodgins, 1991] for dynamic motion synthesis. Later research [Hodgins et al., 1995] applied this method for different tasks like running, bicycling, vaulting and balancing. For high dimensional characters, PD controller tracks the predefined motion curves [Yin et al., 2007].

PD controller is shown in Equation 2.1.

u = K(q − qd ) + dq

̇where u is the control effort, K is the stiffness, qd is the desired or reference position, and d is the damping efficient. PD based methods can run in real-time and generate adaptive responses to small perturbation. But large perturbation response or deviation from the reference trajectory are difficult to achieve.

Most PD based controllers use motion capture data as references. As an alternative, Laszlo et al. [1996] introduced Limit Cycle (LC ) as tracking reference for periodic locomotion animation. Current research studies[Coros et al., 2010, 2009; Laszlo et al., 1996] track fixed limit cycles, such methods share many characteristics with PD , which promise real-time speed, but lack adaptation ability

and the results is stereotype looking.

• Optimization The redundant DOFs make motion planning non-deterministic.

Optimization has been introduced to CMS for this problem. The idea is to choose the “best” one among all the possible motions.

Many merits have been proposed for CMS . For dynamic methods, a reasonable merit is the energy cost E.

t1

fa (t)2 dt

E=

(2.2)

t0

where fa is the active force generated by actuators like motors or muscles. This is introduced to CMS research as the influential Spacetime Constraints [Witkin and Kass, 1988]. It is based on the hypothesis that the natural looking trajectory costs minimum energy and closely relates to the idea of Darwin’s Theory of Evolution.

Optimization based methods produced believable motions for a variety of motion tasks.

Jain et al. [2009] provided an example of locomotion. Macchietto et al. [2009] proposed a method for balance maintaining movement. Liu [2009] proposed a method for object manipulating animation.

Drawbacks of Optimization

Optimization is the current mainstream method for physics based animation. It generated the best motion results in current research. But this method has several drawbacks.

• Numerical Instability and Modelling Difficulties: Optimization methods promise the energy efficiency of the synthesized motion, but there is no guarantee about the convergence speed and stability. In many cases, optimal solution is difficult to find numerically. With such numerical method, the motion result is very sensitive to the accuracy of the model and the proximity of the initial guess. Liu [2005] points out that the primitive spacetime constraint methods only suit high energy motions, like jumping and running. For low energy tasks (such as walking) the results do not look natural.

• Computational Complexity: Optimization with spacetime constraints is a variational problem by nature. For a complex character, it might take prohibitively long time, limiting the application domain of problems to those which are computationally feasible. In addition, little is known about how to reuse a computation result for motion adaptation.

2.1.3 Fix Up

There are many research attempts to make tracking controllers more adaptive or optimization faster. One popular idea is mix the two methods; optimization is done offline for planning the reference trajectory, while tracking controllers are adopted as online controllers.

To simplify the optimization computation, many methods start to incorporate machine learning ideas by training the optimization controllers with motion capture data [Coros et al., 2010; de Lasa et al., 2010; Lee et al., 2010a,b; Levine et al., 2011; Liu et al.,

2010; Wang et al., 2010; Wei et al., 2011; Wu and Popovi ́ , 2010; Ye and Liu, 2010],

Also new methods adopted simplified model for planning [Mordatch et al., 2010].

These attempts may remove some limitations of tracking or optimization, and make them feasible for certain applications. But CMS problems cannot be solved completely in this manner. Learning based methods are complex and sensitive to training examples.

A further question is that stability of controllers cannot be strictly proved. Besides offline optimization does not reduce the computational burden in nature.

## 2.1.4 Biological Constraints

The problems of CMS have also been spotted earlier in biological motor control research. Biological researchers have dropped artificial control ideas long ago, because they violate the biological constraints. Although the mechanism behind information processing remains obscure, some characteristics of biological information processing are well agreed, making CMS methods above questionable [Glynn, 2003].

• Sensing and Control Limitations: Motor control is not only a mechanical problem, but also a complex process involving chemical, electrical and mechanical changes. Many crucial mechanical parameters and variables such as mass, inertia, force, are inaccessible to the neural system and can only be approximated.

Some important control variables (such as torque) are controlled indirectly by the neural system through a complex process. Also body and environmental measurements are noisy and time varying, making methods sensitive to errors unsuitable for biological motor control.

• Neural Computation:

The neural system is powerful, but inferior in speed and accuracy when compared with digital computers. Neural signals are of only hundreds of Hz and their transmission speed is slow. In addition there is a long delay between firing a neural signal and generating force in the muscles. It may cost about half a second from seeing an object to force generation in arm. This makes it impossible for the neural system to carry out the complex computation necessary for realtime optimization.

Following the idea of optimization control, the dynamics of fluid environment and deformable body are more difficult to optimize. But most primitive life forms live in the sea and have limited intelligence.

• Memory Capacity: Some argue that motion control is not based on computation, but based on memory. This avoids the question of computation speed, but it faces the memory capacity problem. Motion varies greatly, if we store the motion in our brain. The capacity problem will arise.

Because of such constraints, researchers have started to look for different strategies.

## 2.2 Motion Primitives

At first, researchers are reminded that logical think or mental conscious plays little role in motor planning. Animals including human exhibit complex motion behaviours after birth or at early ages. Many complex abilities like breathing, heat beating and child bearing are inborn without learning.

Some suggests that motor ability is inborn and organized in blocks [Bizzi et al., 1995,

2002]. Strong evidences come from the experiment where stimulating of a single spinal motor afferent triggers a complete sweeping motion[Bizzi et al., 1995]. A new theory,

Motion Primitive Conjecture, was proposed. In this theory, the building blocks are called motion primitives. Also the theory believes that the number of motion primitives is limited and complex motions are combinations of motion primitives, just like we connect alphabets into sentences.

Motion Primitive Conjecture also provides insight into the question of motion perception. Gallese

et al. [1996] have found action and perception trigger similar reactions in a group of neurons.

### 2.2.1 Dynamic Motion Primitives

The Conjecture of motion primitive is supported by both the behaviour study and anatomy of natural animals. For dynamic CMS , the puzzle is how motion primitives simplify dynamic control problem.

A proposed answer is that motion primitives have some valuable dynamic properties, like stability and efficiency, which mainly comes from natural dynamics. Some researchers point out that motion is closely related to the body structure and environment, and not changed much by the evolution of the neural system, after all the whales swim more like fish than other mammals. Animals do not move the way they want, but rather the way they can.

The new proposition of motor control is that the body and the environment play the most important role in motor control, as they form the basic pattern of motion [Nishikawa et al., 2007]. For the neural system, the responsibility is not planning the trajectory from ground up, but modifying or tweaking basic patterns that meet the purpose constraint without losing the crucial properties. Several theories are proposed for the neural control mechanism.

Experiments have shown that even under the same conditions, the motions still vary.

Some DOFs are not controlled and freely influenced by the environment. Uncontrolled Manifold Hypothesis(UMH )[Latash, 2008] proposes in motor control, trajectory is not the concern, only the final results is.

Equilibrium Point Hypothesis(EPH )[Feldman, 1986] can be seen as a specification of UMH . This idea comes from properties of differential equations. For a dynamic system

̇

x = F (x)

the equilibrium points xe satisfy the condition F (xe ) = 0. EPH suggests the neural

system does not plan motion trajectory, but the position of the equilibrium point.

Impedance Control [Hogan, 1985] refines the idea of EPH by providing an explanation

for effects of the extra DOFs. At an equilibrium point xe ,

F (xe ) = 0

Impedance Control proposed that the extra DOFs provide a way to control the stability

and admittance of the equilibrium point xe . The mathematical presentation is

F (xe + Er ) = KEr

(2.3)

where Er is the offset error vector, K is stiffness matrix or impedance,which determines the stability. Neural system will tune the direction of K according to the purpose, avoiding obstacles or risks. Experiments [Franklin et al., 2007] have shown that the matrix K has anisotropic properties.

### 2.2.2

Neural Control Mechanism

Motor control involves little mental work, and current idea of neural science is that motor control is a low level intelligent activity and can be controlled without brain input. Research studies have proposed several mechanism of tweaking motion primitives.

• In vertebrate animals, Central Pattern Generator (CPG ) serves important functions in locomotion, respiration, swallowing and other rhythm behaviour. Cohen [1988] argues that locomotion is the result of the interaction between neural and mechanical oscillators via a process called entrainment. The neural systems modify the motion by adjust frequency and amplitude of neural rhythmic signal.

• Some research studies find out that motion will change in a uniform manner[Viviani

and Stucchi, 1992],Flash and Handzel [2007] propose modelling motion adaptation through affine transformation. Motion Adaptation can be model as group action. What makes the theory more interesting is the fact that affine transformation group is closely related to the vision system, which implies a close relationship between motor control and vision.

### 2.2.3 Bionic Robotic Research

Ideas from biological research also inspired robotic engineering experiments, which show the feasibility of new control principles. Such robots utilize the natural dynamic rather than the tracking or optimization strategy. Here are some reported researches.

• Limit Cycle in Walking A very important discovery is the bipedal walking can happen without any control[McGeer, 1990]. Under specific condition, a mechanic structure can walk down a slope passively, with natural looking gaits.

And based on this idea, new mechanical system is designed that can walk on plane with simple control strategy [Collins et al., 2005].

• CPG and entrainment The CPG based entrainment is applied for robotic research[Williamson, 1999], the found results show the CPG will boost the system stability and can maintain motion in unpredictable situation. Fukuoka et al.

[2003] has applied CPG for quadrupedal walking.

• Passive based Control The control and mechanics community also starts thinking about passive based control method that utilizes the natural dynamics. Controlled Lagrange [Bloch et al., 2000a,b, 2001]and Controlled Symmetry [Spong1998, 1996] are mathematical rigid method and have been applied to mechanic control and robotics[Spong and Bullo, 2005].

## 2.3 Placement and Contrasts

New biological theories become the foundational idea of MoIT, and moit contribute the theories with mathematical tools.

MoIT introduces topological conjugacy as the foundational modelling theory and unifies different ideas by one mathematical theory.

In MoIT, Motion Primitives are identified by their structural stability.

The principle of EPH and Impedance Control are generalized as attractor and attraction control.

CPG comes from the research of spinal cord, which models the low level control; while the transformation idea comes from research of the cortex, which is a model for high level control. At first sight, Entrainment of CPG and Group Transformation seem very different, but in MoIT, both control principles maintain the qualitative property of natural dynamics. Such unification implies a new control hierarchy framework and has a good biological meaning: The low level control utilize some robust and qualitative measures like entrainment or CPG to boost the stability of motion; while high level control is quantitative and precise, which adapts stable motion for specific purpose.

Based on this framework, motion transition mechanism is developed.