# Adaptive Motion Synthesis and Motor Invariant Theory

# Background

## Motion Synthesis Research

We should know the things we animate. For CMS research, the basic challenge comes from our misunderstanding of the biological motor control system.

#### Data Driven

Data-driven methods are based on ready motion data which are generated by Key-frame or

Motion Capture(Mocap). In practice, motion data are segmented into short time clips. An

animation is generated by selecting motion clips and connecting them together(Parent 2002).

Like other example based methods in Computer Graphics, Data driven methods can generate

good results on if similar motion clips can be found, but it is difficult to generate new motion.

At current, it is also difficult to reuse the motion data, whether adapting the motion data for

a different character or a different scenario. This is usually referred to “ the motion re-targeting”

problem.

Besides the difficulties in generating new motion, management of large motion data is another

problem in practice. The Annotation Database (Arikan, et al. 2003) and the Motion

Graph (Kovar, et al. 2008)are proposed. But because there is no efficient algorithm that understands

motions, catalogue and search of motion data are not trivial task and are still open

questions.

#### Procedure Method

Currently, for physics based motion synthesis research basically have three different ideas.

PD controller.

Some early research applied classical PD controller \citep{Raibert1991} for locomotion synthesis.

Later research \citep{Hodgins1995} applied the same method for different tasks like running, bicycling, vaulting and balancing.

PD control need a reference motion, so the motion is not adaptive

Limit Circle

Limit Circle Control(LCC) \citep{Laszlo1996} provides an alternative method for lower energy locomotion animation.

The LCC theory has been used in explaining passive mechanics.

Compared with Spacetime optimization, LLC methods is more computational efficient method for low energy motion.

In current researches\citep{Coros2009,Laszlo1996}, the limited circle is fixed.

The control strategies are simplified as a state machine controller following a predefined limited circle.

When Limit Circle is fixed, limited circle control falls into trajectory based methods.

Optimization

Because of the redundant DOFs in the body structure, in most cases, there exist many motion solutions for one task.

Optimization methods have been applied to solve the nondeterministic problem.

Among all the solutions in possible motion space, the ``best'' one is chosen as the proper solution:

\begin{equation}

\label{equ:max\_select}

\arg\max\_x V(x), x\in F(q)

\end{equation}

For dynamic methods, a reasonable value function $V$ is the energy cost.



where $F\_{a}$ is the active force generated by actuators like motors or muscles.

This is introduced to CMS research as the influential Spacetime Constraints\citep{Witkin1988}.

It is based on the hypothesis that the natural looking trajectory costs minimum energy.

It is related to the idea of Darwin's Theory of Evolution and the principle of Natural Selection.

In many cases, these methods produced very believable motions.

\citet{Jain2009} provides an example of locomotion;

\citet{BalanceControl} find a method for balance maintaining movement.

\citet{Liu2009} proposed a method for object manipulating animation.

Numerical Stability and Modeling Difficulties:

Optimization can only guarantee the energy efficiency of the resulting motion, but cannot control convergence speed and stability.

Even if the optimal solution is natural looking, it can be very hard to find. Finding the optimal solution depends largely on the accuracy of the model and the proximity of the initial conditions to the final solution. For motion synthesis, an accurate model is very difficult to build, which results in artefacts in the solutions. Liu [2005] points out those space–time constraint methods only suit high energy motions, like jumping and running.

For low energy tasks (such as walking) the results do not look natural, mainly because muscle effects are neglected.

Computational Complexity:

Optimization with space–time constraints is a variational problem by nature. For a complex body structure, the performance of even current state of the art numeric methods is prohibitively slow, 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.

### Biological Motor Control

Recently biological research has a different idea about motor control.

The theory comes from tradition artificial systems are highly unlikely the idea for biological system. This is because they neglected the biological constraints.

##### Biological Constraints

Although the mechanism behind information processing remains obscure,

some characteristics of biological information processing are well agreed.

These characteristics make optimization control methods questionable.

Here we list several major questions\citep{Glynn2003}.

Sensing and Control Limitations:

Motor control is not only a mechanical problem, but also a complex process. Many crucial parameters and variables of the biological system are inaccessible

to the neural system (such as mass, inertia, force) and can only be approximated. For important control variables

(such as torque), the neural system has no direct control.

In addition to this, body and environmental measurements are

noisy and time varying, making methods that are sensitive to

errors unsuitable for biological motor control.

Neural Computation:

The neural system is powerful, but is inferior in speed and accuracy when compared with a digital computer. Signal transmission speeds are slow — there is a long delay between firing a neural signal and generating force

in the muscles . This makes it impossible for the neural system to carry out the complex computation necessary for real–time optimization.

Human’s body structure goes through big change thought lifetime.

Memory Capacity:

Some people argue that motion is not computed, but we store all the possible motor control ability in our memory, then when execute a motor task, we just access the memory for the proper motor control command.

This idea may helps to drop the question of computation speed, but it faces another problem, the memory capacity.

Motion varies greatly, if we store the motion in our brain, the problems is the memory capacity.

Motion Primitives

Following the idea of optimization control,

the dynamics of fluid environment and deformable body structure are more expensive to optimize.

But most primitive life forms live in the sea and have limited intelligence.

And many animals include human exhibit complex motion behaviours at very young age, before the intelligence system is fully developed.

If we expand our view port, many complex motion abilities like breathing, heat beating and child bearing are inborn.

There is no need for learning or intelligent effort.

Also we find out that the motion style is not changed by the evolution of the neural system, after all whale swim more like fish than other mammals

A consequence of this theory is that animals don’t move the way they want, but rather the way they can.

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].

These basic patterns are called motion primitives [Poggio and Bizzi 2004],the number of motion primitives is quite limited

Planning or Tweaking

Despite the complexity of body structures and environment, the natural motor control strategy seems relatively simple, involves little computational work, and outperforms optimization methods.

The current idea of biology research is that motor control is a low level intelligent activity and can be controlled with primitive neural structure without brain input.

In many animals, the active neural structure in motor control is the Central Pattern Generator (CPG) which generates rhythmic signals.

Cohen [1988] argues that human locomotion is the result of the interaction between neural and mechanical oscillators via a process called entrainment.

Neural systems modify the motion by changing frequency and amplitude of the neural signal.

Some research proposes the tweaking effects of motion can be treated as kind of transformation. And use affine transformation to model motor tweaking effects.

Observation and Perception

For motion perception, we have found some result. One is that all the motion seems modified in a quite regular manner.

There is an uniform change of motion, like the speed and curvature of motion curve is close related.

Some recent research identify this as some motion properties can by modelled with affine transformation.

Some researches also propose that the affine transformation has greatly related to our vision system. This means maybe our ability to identity motion is closely related to our ability to identify object in spite of its different position in space.

#### Motor Control Objective

Even the idea of following predefine trajectory is questioned.

The observation of blacksmith's hammering motions show that even under the same conditions, the motions still vary.

An explanation is the neutral system doesn't control all the DOFs.

Some DOFs are not controlled and freely influenced by the environment.

This is the Uncontrolled Manifold Hypothesis(UMH)\citep{latash2008neurophysiological}.

In this viewpoint, the result of motion planning is not a trajectory, but a space of valid trajectories. As long as the motion task is finished, neural system may not care how it is carried out.

Equilibrium Point Hypothesis(EPH)\citep{Feldman1986}can be seen as a further development of UMH.

This idea comes from properties of differential equations.

For a dynamic system

\[

\dot{q}=H(q)

\]

the equilibrium points $q\_{e}$ satisfy the condition $H(q\_{e})=0$.

Equilibrium point is the final position of the motion curve.

EPH suggests that what the neural systems controls is not trajectory, but the equilibrium points.

Impedance

Impedance Control \citep{hogan1985ica} refines the idea of EPH by providing an explanation for effects of the extra DOFs.

At an equilibrium point $q\_{e}$,

\[

H(q\_{e})=0

\]

Impedance Control proposed that the extra DOFs provide a way to control the stability and admittance of the equilibrium point $q\_{e}$.

The mathematical presentation is

\begin{equation}

H(q\_{e}+Er)=K

\end{equation}

where $Er$ is the offset error vector, $K$ is stiffness matrix or impedance.

If $K$ positive, $q\_{e}$ is unstable, characters will change his posture;

if $K$ is negative, $q\_{e}$ will be stable, posture can be maintained.

if the value of $K$ is large, the posture will be more stiff and rigid.

if $K$ is small, posture will be more gentle, and perturbations will cause a large offset error.

Neural system will tune the direction of $K$ according to the motion purpose, such as avoiding obstacles and risks.

Experiment \citep{Franklin2007} shows that the matrix $K$ has anisotropic properties.

The idea is well supported by biological research but the method is computational expensive.

His idea is using Lie Group, to transform the one motion into another,

This method can achieve the same effect of impedance control but is more computational efficient.

Bionomic robotic research Evidence

Biological research idea greatly inspired the engineering experiment.

Some researches begin to focus on utilizing the natural dynamic and use as little control as possible with the hope that this method will produce more efficient robots. And some significant result has been reported

Passive Walking

A very important discovery is the bipedal walking can happen without any control. When putting a mechanical toy with human like body structure, it can walk down slope without any control effort. And based on this idea, new mechanical system is designed that can walk on plane with simple control.

CPG in locomotion

Also the CPG based entrainment is applied for robotic research, the finding results show the CPG will boost the system stability and can maintain motion in unpredictable situation.

Symmetric based Control

The idea of Symmetry is also well exploit in Mechanical research.

For mechanical view port, Symmetry has more concrete meaning.

Like energy preserving or momentum preserving.

The idea of Symmetry is also used in control; some techniques are called “Energy Shaping”.

#### Our Research

This biological research idea greatly influenced our motion synthesis research.

While in our research, we unified the different method under a new framework.

We argue that the motion primitives and equilibrium point are closely connected; basically, we can identify motion primitives by exploring the equilibrium point type of the underlying dynamic equation.

While for tweaking, CPG and Transform have different role. The role of CPG is providing stability and maintains the equilibrium type, transformation will have no effect on stability, and its role is place the equilibrium point at proper position.

A question is how the CPG and boost stability. Our finding is that motion primitives have a special equilibrium type rather the one we see in the ship example.

The equilibrium point of motion primitives is a periodic circle, called limit circle. Entrainment can maintain its oscillating behaviour thus maintains the qualitative property.

The original impedance control is based on finding the required Jacobin matrix, which is computational expensive, while we found the symmetry based method can have the same effect.