Introduction

# The Challenge

Character Motion Synthesis CMS research aims at generating motion for virtual characters.

It is a topic of significant value in theory and application.

Besides major applications in the media industry, where both computer games and animation films depend heavily upon character motions for storytelling, current research also finds its applications in user interface design, psychology, sports and medicine.

The challenge of CMS is not to make characters move, but to make them lifelike.

Underneath this challenge is human's marvellous ability of motion perception.

In real life, motions are very similar; while from the varieties in motion details, humans can infer mental states, health conditions or the surrounding environment.

Human motion perception has some very peculiar property.

Some awkward artefacts are spotted instantly even they are physically feasible, while many physical impossible motions are accepted as realistic and entertaining.

Nowadays in industry, high quality motions are mainly generated by manual work.

Very often, characters are complex and contain a large number of joints, making animation a tedious work. Making it worse, reusing motion animation is also difficult and prone to artefacts.

High level animation tools are badly needed.

Real life motions highly interact with the environment.

Physics based method is most important research endeavour at current.

Besides the addition of the dynamic interactive responses, it is expected the elimination of artefacts that violating physics will make motions more natural looking.

However, this paradigm faces many difficulties; dynamics of biological system are much more complex than artificial system, attempts to dynamic simulation biological system face inhibitive computational cost and modelling difficulty.

In fact, such problems have been identified by biological researchers earlier.

Motor Control and Motion Perception are close related.

Difficulties in CMS reflect the inferiority of artificial control method.

The peculiarity of motion perception and control suggests biological systems may adopt a different principle.

To generate natural looking motion, it is worthwhile to synthesize motion following the biological motor control principle.

This thesis is founded on new ideas from biological research.

# Agile Animals

Although animals have fascinated us for thousands of years, we still don't fully understand how they move.

Animals are very different from artificial machines and such comparisons may reflect the biological motor control principle.

Degrees of freedom

From Mechanical perspective, animals have many more DOFs than their artificial counterparts.

An artificial ship can be approximated by a simple rigid body; while a fish has the flexible vertebrae of tens of DOFs.

In principle, the extra DOFs admit more variations for adapting the environment.

But for the control system, too many extra DOFs are a disaster because of the computational burden.

For a human to take one step, the neural system controls more than 600muscles.

With nowadays computer, solving the dynamics directly will require inhibitive long time.

Versatility

Most artificial machines are designed with a single purpose, while animals are capable of unlimited tasks.

Many biological functions which often are neglected by CMS research, such as the feeding, breeding, language and vision, depend on motor control.

Besides walking, swimming and many other styles of locomotion, we utilize many tools, such as cars, skate, bicycle and tennis.

Follow traditional control methods, it seems unlimited resources need to be allocated for motor control, while biological research shows motor control cost very little mental resources.

Performance

Although the problem of biological motor control is more complex, the resulting performance surpasses artificial machines in many aspects.

Natural motions are more

Robust

Human can maintain walking stability on tough terrains inaccessible for vehicles.

Manoeuvrable and speedy

Typical modern aeroplanes will travel 32 body length/sec and yaw 720 deg/sec at max.

While pigeons may travel 75 body length / sec, yaw at about more than 5000 deg/sec.

Energy Efficient

The energy consumed by human walking is only 5% of that for the world famous humanoid ASIMO.

# Motor Invariant Theory

## Utilize Natural Dynamics

Biological Motor Control has achieved a delicate balance of robustness, controllability and energy efficiency.

The real-time performance may further suggest that the biological method is simple and requires little computational load.

These are the dreaming properties for CMS research and their explanation forms the gene of the thesis.

Interactions between the body and environment pose complex dynamic problems for motor control.

In most CMS research studies, such natural dynamics are treated as noises or perturbations to pre-planned motion command, and the effects of natural dynamics are cancelled by control effort.

But from the evolution perspective, the mechanical structures are product of natural selection which has evolved with the environment for millions of years.

They are advantages rather than handicap.

Without considering the stability, energy efficiency and real-time reaction can be easily achieved if the motion is totally governed by natural dynamics and requires no control effort.

A new idea is that motor control is based on the natural dynamics.

Neural system plays a minor role in planning; it just utilizes the natural dynamic properties.

Motor Invariant Theory (MOIT) is a proposed idea of how to utilize the natural dynamics in a systematic manner.

## Motor Invariant Theory

This thesis proposes a new idea for the underlying reason for superiorityof biological motor control.

The insight is thatin the process of motion adaption, some valuable properties of natural dynamicsare kept invariant.

The conjecture is that: instead of detecting and cancelation all kinds of perturbations, biological motor control relies on the invariance of natural dynamic properties for motion success.

This is theMotor Invariant Theory.

MoIT incorporates the idea of motion primitive and provides an explanation in dynamics.

In dynamics, invariant properties are stable properties.

From a dynamic perspective, not all the motions generated by natural dynamics are stable, only a few are stable,which can be utilized motion templates and become motion primitives.

The remaining question is how the motor control system utilizes the templates to synthesize motion.

The MoIT proposes that when facing a new situation, a human does not solve motor control from ground up;motor control system utilizes successful experience in similar situations.

In dynamics, adapted motions are qualitative the same with the motion primitives or templates, and there is a one-one mapping relationship between the adapted motion and the motion primitive.

This similarity in dynamics is topologicalconjugacy.

In dynamic CMS research, a motion is represented by a curve x(t) parameterized by t.

x(t) is the solution to the equation (Equation 1.1) that describesthe body and environmentdynamics.

x˙ = F(x) (1.1)

To illustrate adaptation, we define a transformation T that acts on the space of x.

˜x = T(x)

In this way, each equation can be described in two coordinate systems: one by $x$ and one by $\tilde{x}$.

As an example, Equation 1.3 describes the same dynamics as Equation 1.2 in a different coordinate system.

x = F(˜x) (1.2)

x˙ = F˜(x) (1.3)

Since such two equations describe the same motion in different coordinate systems, the solution of one equation can be achieved by transforming the solution of the other.

Suppose x′(t) is the solution to Equation 1.3 and ˜x(t) is the solution to the Equation 1.2, then we have:

x′(t) = T−1(˜x(t))

Equation 1.2 and Equation 1.1 are the same, thus :

˜x(t) = x(t)

Then we have

x′(t) = T−1(x(t))

By transformation, we obtained a new motion $x'(t)$ from $x(t)$.

The transformation method has many advantages:

It is less computational expensive and keeps many important properties untouched.

For example, if the original dynamics is stable, then the transformed dynamics is also stable.

If there exists continuous one-one mapping between the two dynamic equations, then the two are topological conjugate.

This relationship is presented by F ≃ ˜ F.

F and ˜ F are called analogous systems, which share the same topology structure.

The existence of one-one mapping isthe necessary and sufficient condition for topological conjugate, thus there are two basic approaches for motion adaption.

Transformation can be specified explicitly or implicitly by maintaining the topology.

If the perturbation does not violate the topology, the corresponding one-one mappingwill modify the motion without changing it qualitatively.

In dynamics,the topology preserving ability is an intrinsic property of many dynamic systems: *structural stability*.

One strategy of motor control is to enhance the structural stability.

With this approach, the qualitative property is preserved and there exists aone-one mapping relationship, but finding out details of motion will be difficult or computationalexpensive.

Thereforethis approach is qualitative.

In **MoIT**, this approach models the involuntary motion adaptation which is low level function of neural control system.

The topological structure is one important property should be kept invariant, thus become a motor invariant in MoIt: the Global Motor Invariant.

Also if the transformation is known, then the two systems must be topological equivalent.

This method modifies motion with precision and **MoIT**applies this idea for high level voluntary motor control.

In many situations, to achieve a desired transform $T$, control effort needs to be applied.

For this method, choosing a proper transformation T is the most challenging question.

In **MoIT**, selection of T is based on two principles.

•Parameters of transformation T should be easy to detect and formulated, which meets the biological sensing and computational constraints.

•The transformation T should be energy efficient.

For differential dynamic system, some transformation explores the natural dynamics and requires little or no energy input.

Some quantitative properties will be unchanged during transformation, which are called

*Local Motor Invariant* Motion Adaptations that are precise and voluntary controlledare called *Transform Adaptation.*

Although new mathematical language seems obscure at first glimpse, the properties that the mathematical language describes are universal in physical world, with or without life.

The underlying idea is intuitive and can be explained well throughcommonly observed phenomena.

Although new mathematical tools seem obscure at first glimpse.

The underlying idea is intuitive and can be explained well by commonly observed phenomena.

## The Floating Ship: An example of Stability

The floating ship example shows the idea of structural stability and topological conjugacy.

In real life, ships floating on the wave are typically taller than they are wide, as shown in Figure 1.1.

An interesting question is how the ship maintains its posture.

Through analysing the topology and structural stability, we see that it is trivial to maintain posture.

This conclusion applies to different ships since their dynamics are qualitative the same, or topological conjugate.

### Dynamics

The sway motion of the ship shown in Figure 1.1 can be described by Equation 1.4

Jq¨+ dq˙ = τ(q)g+ τ(q)b + τu (1.4)

whereq is the swaying angle.

J is the inertia, d is the damping coefficient, and τg,τb,τuare the corresponding the torques of gravity, buoyancy and external control.

When the ship is on the sea, the motion is governed by the two forces, the buoyancy b and gravity g.

Whenτu = 0, the dynamics isgovernedby its natural property. Such a system is autonomous.

To make it consistent with discussions in following chapters, Equation 1.4 is reformulated.

Defining the *state* variable **x** = [q, q˙], then Equation 1.4 becomes

**x**˙ = FJ,d(**x**) + Du

whereF is a function of **x**, the subscripts J and d are*system parameters*,

D is a matrix,which describes how the control effort is applied, and u is *control input*, for this example u is τu

### Equilibrium Postures

A ship will only rest when τg + τb + τu = 0, which are called Equilibrium Postures.

The only two possible ones are show in Figure 1.2 and Figure 1.3.

The two postures are different, illustrated with the phase plot.

On the phase plot, the horizontal axis represents q; and the vertical axis represents velocity q˙.

The motion of the ship is shown as a curve on the phase plot, which is called flow.

The posture in Figure 1.2 is attractive or stable, for if a small perturbation moves the ship away from the left posture, it will return to the equilibrium posture automatically as shown in Figure 1.4.

Whereas the posture in Figure 1.3 is *repelling* or *unstable*, if being slightly moved away from the equilibrium posture, the ship will move away further, as shown in Figure 1.5.

### Trivial Task

All the flows form the *phase portrait* of the dynamic system.

The discovery for the phase portrait is that allthe flows start from the repelling posture and ends at the attractive posture.

Several example curves are show in Figure 1.6.

This means no matter what the current posture is, the ship will return to the normal stable posture automatically.

This is an intrinsic property of the natural dynamics, and thanks to this, balancing are a trivial task which requires no control effort.

This property is determined by the qualitative structure designcriteria, making the centre of buoyancy above the centre of gravity.

### Generalization of the Ship Example

This conclusion is independent of the shape, size, weight or material of the ship.

In general cases, the samewave perturbation will result in different sway motions for different ships.

However, as long as the qualitative structure design criteria are maintained, balancing remains “easy”.

The phase portraits of all the ships share following properties.

•one repelling point

•one attractive point

•all flows start from repelling point and end at the attractive point.

In mathematical terms, all the phase portraits share the same topology structure of Figure 1.7.

This phenomenon illustrates the principle idea of motion adaptation in MoIT.

When the variations among individuals or situations result in motion variation,the qualitative dynamics or topological structure of the dynamic system remains invariant.

## The Mass Spring System: Symmetry Transformation

Despite the complexity of body structure, biological motor control is fast and accurate.

Such quantitative properties poseanother puzzle inmotor control research, as solving the complex dynamics directly would require prohibitive long computational time and excessive mental resources.

**MoIT** proposes a new method to achieve the speed and accuracy of motor control.

An efficient control strategy is based on the idea of transformation.

Without solving the dynamics, new motions are achieved through transformingtemplate motions.

To keep the motion natural looking, control system chooses the transformation directions that are energy efficient, or in another term,allowed by the natural dynamics.

Such ideas can be illustrated by the following mass spring example, shown in Figure 1.8.

The mass spring system is selected for it captures some important properties of biological dynamics.

The compliantactuators of muscles work like springs, and rigid bones are modelled as mass.

### Dynamics

The canonical equation of mass spring system is

¨q + q = 0. (1.5)

whereq is the offset distance.

By defining the *state variable*, **x** = [q, q˙], Equation 1.5 can also be reformulated in the form as

**x**˙ = F(**x**)

Figure 1.9 shows two flows passing through different state x and x’ on the phase plot.

### Symmetry and Transformation

The mass spring system has some “symmetrical properties”.

Different flows share thesame circle “Shape”.

Without solving Equation 1.5, new flows (solid line) can be obtained by scaling the original(dotted line) flow.

From a mechanical viewpoint, this is because the flows of mass spring system are energy preserving.

We can define the energy function

E =1/2(mq˙2 + kq2)

wherek is the stiffness, m is the mass.

When m = 1, k = 1, since E is a constant, we can take E = c, and obtain q2 + ˙q2 = 2c, which is the implicit function of a circle.

Therefore given template flow that passes through **x**, for the state **x**\_, by checking the energy, the scale transformation from red to green can be worked out.

In this manner, we obtained the future motion after **x**\_, without solving the dynamics.

### Dynamic Perception and Local Motor Invariant

The idea “transformation and symmetry” may shed light on dynamic perception.

It is highly unlikely animals can solve Equation 1.5 to understand mass spring system.

As an alternative, the dynamics can be encoded in a different manner: a motion template and the symmetry property.

If so, observed motions can be validated by being checked against motion templates in our memory.

To make it better, it is even unnecessary to working out the transformation, it is enough just to check some property invariant under transformation.

For the mass spring system example, we can check the “shape” of the flow, or from a mechanical perspective, checkthe energy preserving property.

The invariant properties like energy preserving or shape can be quantitative measured, they are invariant only when system flows move in a specific direction, thus are called *Local Motor Invariant*.

# Contribution

Compared with current CMS methods, the new approach has several advantages:

1 More Types of Adaptation

Most dynamic methods only focus on generating responsive motion to dynamic perturbation. Adaptations across different characters are treated as a separate research topic(motion re-targeting) with different method.

MoIT unifies different adaptations in one theory.

The mathematical idea of topology conjugacyincorporates both motion re-targeting and perturbation responses in a unified framework.

Thus MoIT can generate more types of adaptation.

2. Better Usability.

Formany CMS methods, each DOF is controlled independently.

When modifying motions, animator has to modify each DOF, which is tedious work.

In MoIT , adaptation is achieved by applying transformation.

Each transformation can be parameterized by one parameter.

By specify only one parameter for the transformation, control inputs of all DOFs are modified automatically, which is more user-friendly.

3. No Reference Motion Needed

MoIT relies on the dynamic equation of body and environment.

Motion Capture Data is not needed as reference.

In situations, this method can generate new motions that cannot be captured.

4. Computationally Efficient

This motion synthesis approach requires little computation time and memory, it suits real-time applications.

5. Dynamic Motion Transition

Dynamic motion transition is developed upon solid theory foundation.

Because of its biological foundation, algorithms and simulation results of MoIT might

shed light into biology research. Some conclusion and control techniques can be

treated as candidate theory that needs further verification.

1. Motion Primitive is an old idea in biological research, but there is no agreement

on the definition and underlying reason. Biological research has tried to identify

motion primitive by exploring the neural anatomy, EMG signal or muscle

activation pattern.

MoIT explains the motion primitive from dynamic viewpoint. This theory is

more complete. Besides identification, it also answers why certain motions are

primitives and others are not, how many motion primitives we have, and where

they come from.

2. One supporting theory of motion primitive is the muscle synergy: Generat-

# Hard working boys