Chapter 1

INTRODUCTION

# 1.1 The Challenge

Character Motion Synthesis (CMS ) research aims at generating motion for virtual characters. It is a topic of significant value in terms of theory and application. Besides major applications in the media industry, where both computer games and animation films depend heavily upon character motion for storytelling, current research also has applications in user interface design, psychology, sport and medicine.

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

Underlying this challenge is the marvellous human ability of motion perception. In real life, people’s motion is very similar, yet individuals vary considerably. From the varieties in motion details, humans can infer mental states, health conditions or the surrounding environment. Human motion perception has some very peculiar properties.

When watching a film with computer generated characters, some awkward artefacts are spotted instantly even though they are physically feasible, while many physically impossible motions are accepted as realistic and entertaining.

Nowadays in industry, high quality motions are mainly generated manually. Very often, characters are complex and contain a large number of joints, making animation tedious work. To make it worse, reusing motion animation is also difficult and prone to artefacts. Therefore high level animation tools are badly needed.

Real life motions interact extensively with the environment. Currently, the most important research endeavour is the physics based approach. Besides the addition of the dynamic interactive responses, it is expected that the elimination of artefacts that violates physics will make motions more natural looking. However, this paradigm faces many difficulties: dynamics of biological systems are much more complex than artificial systems; attempts to dynamically simulate biological system face prohibitive computational costs and modelling difficulties. In fact, such problems have already been identified by biological researchers.

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 very different principle. To keep motions natural looking, it is worthwhile to synthesize motion following the biological motor control principle. This thesis is founded on new ideas from biological research.

# 1.2 Agile Animals

Although animals have fascinated us for thousands of years, we still do not 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 (DOFs). From a mechanical perspective, animals have many more DOFs than their artificial counterparts. An artificial ship can be approximated by a simple rigid body; whereas the flexible vertebra of a fish is made up of tens of DOFs.

In principle, the extra DOFs allows for more variations in adapting the environment. However, for the control system, too many extra DOFs become a disaster because of the computational burden. For a human to take one step, the neural system controls more than 600 muscles. Even with nowadays computer, solving this dynamics directly would spend thousands of hours.

• Versatility. Most artificial machines are designed with a single purpose, while animals are capable of unlimited tasks. Many biological functions which are often neglected by CMS research, such as 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, skates, bicycles and tennis rackets.

Following traditional control methods, it seems that unlimited resources need to be allocated for motor control, while biological research shows motor control requires very few 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

1. Robust: A human can maintain walking stability on rough terrains which would be inaccessible for vehicles.

2. Manoeuvrability and speed: Typical modern aeroplanes travel at a maximum of 32 body length/sec and yaw at 720 deg/sec. While pigeons may travel at 75 body length/sec, yaw at about 5000 deg/sec.

3. Energy Efficiency: The energy consumed by a walking human is only 5% of that for the world famous humanoid ASIMO.

# 1.3 Motor Invariant Theory

## 1.3.1 Utilizing 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 the explanation that how biological systems achieve this forms the genesis of this thesis.

At first, interactions between the body and environment pose complex dynamic problems for motor control. In most CMS research studies, effects of natural dynamics are treated perturbations for planning, and are cancelled by control effort. However from an evolutionary perspective, the mechanical structures are a product of natural selection, which has evolved alongside with the environment for millions of years. These structures are an advantage rather than a handicap. Without the need to consider stability, energy efficiency and real-time constraints, motion can be synthesized by natural dynamics without any control effort. Thus a new idea is that motor control is based on natural dynamics. The neural system plays a minor role in planning; it simply utilizes natural dynamic properties. From this perspective, the key question to be answered by

Motor Invariant Theory (MoIT ) is how to utilize the natural dynamics in a systematic manner.

## 1.3.2 Motor Invariant Theory

This thesis proposes a new idea for the underlying reason for superiority of biological motor control. The insight is that in the process of motion adaptation, some valuable properties of natural dynamics are kept invariant. The conjecture is that: instead of detecting and cancellation all kinds of perturbations, biological systems rely the success of motor control on the certain invariant properties of natural dynamic This is Motor Invariant Theory(MoIT ).

MoIT incorporates the motion primitive conjecture. 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 as templates and become motion primitives. The following question is how the motor control system utilizes these templates to synthesize new motion.

MoIT proposes that when facing a new situation, humans don not solve motor control problem from ground up, our 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 topological conjugacy.

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 describes the dynamics between the body and environment.

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 x. As an example, Equation 1.3 describes the same dynamics as Equation 1.2.

̃

Thus for each motion, we can obtain two equations of the transformed state ( ̃ ) and

x

original state x (Equation 1.3).

̇ (1.2)

x = F ( ̃)

̃

x

̃ (1.3)

x = F (x)

̇

Since such two equations describe the same motion, the solution of one equation can be achieved by transforming the solution of the other. Supposing 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 ( ̃(t))

x

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 much less computational expensive and keeps many important properties untouched. For example, if the original system F is stable, then the transformed system F should also be stable. In mathematical language, if there exists continuous one-one mapping between the two dynamic systems, 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 is the necessary and sufficient condition for sharing topology structure. Based on this, two approaches for motion adaptation are developed. Transformation can be specified explicitly or implicitly by maintaining the topology.

If the perturbation does not violate the topology, the corresponding one-one mapping will 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. By this approach, when the qualitative property is preserved by the control system, the one-one mapping that transforms motions is automatically specified. However, in many cases, finding out details of one-one mapping maybe be difficult or computational expensive. Therefore this 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 that 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. Therefore, another approach is to directly specify the transformation. This method modifies motion with precision and MoIT apply it for high level voluntary motor control. In many situations, to achieve desired transform T , control effort needs to be applied. When applying this method, how to a proper transformation T is the most challenging question.

In MoIT , the 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.

When specifying transformation directly, some quantitative properties will be unchanged during transformation, which are Local Motor Invariant

Although the new mathematical language seems obscure at first glimpse, the properties that it describes are universal in physical world, with or without life. The underlying idea is intuitive and can be explained well through commonly observed phenomena.

## 1.3.3 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 this 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

J q + dq = τ (q)g + τ (q)b + τu

̈

̇

(1.4)

where q is the swaying angle, J is the inertia, d is the damping coefficient, and τg ,τb ,τu are the corresponding the torques of gravity, buoyancy and external control.

When a ship is on the sea, its motion is mainly governed by the two forces, the buoyancy b and gravity g. If τu = 0, the ship motion is totally governed by the natural dynamical forces. Such a system is autonomous.

To make it consistent with discussions in following chapters, Equation 1.4 is reformulated. By defining the state variable x = [q, q], then Equation 1.4 becomes

̇

̇

x = FJ,d (x) + Du

where F 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 , which is 0.

### Equilibrium Postures

A ship will only rest at the postures where τg +τb +τu = 0, which are called Equilibrium Postures. The only two possible ones are shown in Figure 1.2 and Figure 1.3.

However, the two postures are different, which is illustrated with the phase plot. On the phase plot, the horizontal axis represents q; and the vertical axis represents velocity

q. On the phase plot, the motion of the ship is shown as a curve, 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.

Figure 1.4: Phase Plot of the Stable Posture

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

### Trivial Task

All the flows form the phase portrait of the dynamic system, which illustrates all the possible motions. The discovery is that all the flows start from the repelling posture and end at the attractive posture. Several curves are shown 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 is a trivial task which requires no control effort. This property is determined by the qualitative structure design criteria that the centre of buoyancy is above the centre of gravity.

Figure 1.6: Global Properties of the Flows: All the curves start from the repelling posture (Red) and end at the attractive one (Blue)

### Generalization of the Ship Example

This conclusion is independent of the shape, size, weight or material of the ship. In general cases, the same wave perturbation will result in different sway motions for different ships. However, as long as the qualitative structure design criterion is 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

This phenomenon illustrates the principal idea of motion adaptation in MoIT . When

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

## 1.3.4 The Mass Spring System: Symmetry Transformation

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

Such quantitative properties pose another puzzle in motor 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 strategy is based on the ideas of transformation and symmetry. Without solving the dynamics, new motions are achieved through transforming template 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 compliant actuators of muscles work like springs, and rigid bones are modelled as mass.

### Dynamics

The canonical equation of mass spring system is Equation 1.5

q + q = 0.

̈

(1.5)

where q 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 states x and x′ on the phase plot.

Figure 1.9: Mass Spring Phase Plot: two flows pass through different states (x and x′

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Symmetry and Transformation

The mass spring system has some “symmetrical properties”. To an intuitive eye, different flows share the same circle “Shape”. Without solving the Equation 1.5, new flows (solid ones) can be obtained by scaling the original (red) flow.

From a mechanical viewpoint, this is because the flows of mass spring system are energy preserving. To see this, we can define the energy function

1

̇

E = (mq 2 + kq 2 )

2

where k is the stiffness, m is the mass. When m = 1, k = 1, since E is a constant, let us make E = c, and we obtain

q 2 + q 2 = 2c

̇

which is the implicit function of a circle.

Therefore, given the template flows that pass through x, for the state x′ , its flow is of the cycle shape with different energy. 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 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 our memorized motion templates.

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, check the 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.

# 1.4 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 motions to dynamic perturbations. Adaptations across different characters are treated as an independent research topic (motion re-targeting) and tackled with very different methods. MoIT solves the two problems with one approach. The mathematical idea of topology conjugacy incorporates both motion re-targeting and perturbation responses in a unified framework. Thus MoIT are capable of types of adaptation.

2. Better Usability. For many 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, making this method more easy to use.

3. No Reference Motion Needed MoIT relies on the dynamics of body and environment. Motion Capture Data is not needed as reference input. In situations, this method can generate new motion 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 Transitional motion can also be simulated dynamically, and such methods are developed upon solid theory foundation.

Because of its biological foundation, algorithms and simulation results of MoIT might shed light on biology research questions. Some conclusions and control techniques developed in this thesis provide alternative ideas for biological motor control, and potential may have theoretical value.

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 examines the motion primitive from the dynamic viewpoint. The discovery and conclusion are more logical and complete. Besides pointing out a motion primitive, MoIT also explain why certain motions become primitive, how many primitives exist, and how they formed.

2. Many biological research ideas like CPG and invariant based perception are proposed empirically. To be a complete theory, much necessary detailed information is still missing. As a contrast, MoIT is based on rigid mathematical theory, for many biological ideas, MoIT provides workable mathematical machinery.

# 1.5 Organization of the Thesis

This thesis is organized as follows.

In Chapter 2, previous research on motion synthesis and biological motor control are discussed, which are the motivation and justification of MoIT .

In Chapter 3, Qualitative Dynamics is introduced to explain motion primitives. Biological based methods for maintaining the global motor invariant are developed.

Chapter 4 focuses on the idea of Local Motor Invariant and Symmetry. Lie Group Theory is introduced to analyse the symmetry properties in motion dynamics. Symmetry

Controllers are developed to provide necessary energy input for adapting motions.

Chapter 5 discusses the combination problems. For a single motion primitive, strategies are developed to preserve both the global and local motor invariant simultaneously.

Motion primitive transition is discussed. Methods for combining motion elements into more complex motion are developed. As an animation system, the software architecture and work flow are discussed at the end.

Chapter 3, 4, 5 lay the theoretical foundation of MoIT . Following chapters provides experimental verification.

Chapter 6 focuses the synthesizing adaptive motions for one primitive. Bipedal walking is chosen as the example, which is commonly observed but proposes great challenges for current CMS research. Methods based MoIT successfully boost the stability and generate adaptive gaits, and further validation shows the synthesized gaits comply with natural observation.

In Chapter 7, motion transition is discussed. A new balancing motion primitive is developed. Adaptive transitional motions from stance to walk and walk to stance are generated dynamically.

In Chapter 8, extensions of motor invariant theory to more complex characters are discussed. Three strategies are developed to simplify the problem for different situations.

This thesis ended with Chapter 9. After discussion of new finding of this research, some new questions and ideas for graphics and neural science are proposed for further research.