Chapter 9 CONCLUSION AND FURTHER WORK

# 9.1 Conclusion

Physics based Method for synthesizing Character Animation has attracted lots of research interests in recently years. However, efficient methods for natural looking motion are still out of reach. This is mainly because of the complex structure of body dynamics. For Physics based methods, the planning and inverse dynamic problem is very challenging. Optimization or Data Driven based method are proposed, but such methods often require inhibitive computational time or extensive motion data that easily runs out of memory.

For a different perspective, the underlying question of motor synthesis research is how animals move in the complex and variable environment. This problem is more valuable and interesting. In fact, it attracts even more researchers beyond the computer graphic community. Biological and Robotic Research investigate the motion control problem from a very different perspective, and they discover some more important properties which may be more crucial for understanding animal motion than visionary properties that mainly concerned by graphic researchers. They have identified the limited neural activity, stability and energy efficiency of motor control.

The current idea from Biology of Science and Robotic Engineering experience rejects the major ideas of Graphic Researchers, because the sensing, computation and actuation systems of real animals are not suitable for optimization or database management. Animals in nature must adopt a very different strategy for moving. An inspiration from biology and robotic research is that the complexity of body dynamic may have a reason. The complexity of body dynamic is not to challenge the neural control system, but on the contrary, the complexity reflects the sophistication of design. A sophisticate mechanical system may ease the control of many daily motion tasks. The new idea is that in fact most of the motion problem has been solved already by the nature, which equips animals with very handy mechanical apparatus, for adjusting motion behaviour to its special purpose; animals only modify the basic motion behaviour in a brilliant manner.

These ideas are the inspiration of this research. In this research, animation method is developed with a consideration of the biological facts. We believe that if our animation method follow the biological principle, potentially our characters in the virtual world will move and reactive in a more natural manner. Such a goal has been partly achieved in this research.

Furthermore, there are more valuable results from the researching process. By adopting the synthesizing approach, when developing simulation program, the intuitive biological ideas are put to test for their computational efficiency and logical soundness. In this process, new mathematical interpretation and algorithm are proposed. The new idea proposes more detail information in the motor control process. If this can be approved by further biological research and experiment, it is more detailed and accurate compared with current biological ideas, it even can be used to control a real robot. These new ideas are summarized as the Motor Invariant Theory.

Motor Invariant Theory are composed of several interconnecting ideas, they are unified by on a very different perspective dynamics. In our eyes, the traditional force -motion perspective is not proper for understanding natural dynamic, because it provides little information about stability, energy efficiency of motion.

In motor invariant theory, phase space is introduced and a dynamic system is transformed into a geometry structure. Based on this, motion dynamics studied from geometrical perspective with many geometrical tools.

On phase space, the dynamic system is divided into different regions. There is an attractor in each region which attracts all the surrounding states into it. Motor Invariant Theory proposes that animal motion utilizes these attractors for motion. This is because attractors promise stability, energy efficiency and easy control for motion. The idea of organized motions by blocks have biological research support, this is the motion primitive hypothesise. And the idea of utilizing attractor for motion has been proposed by equilibrium point hypothesis. Such idea may be new for graphic researchers but the principle are long established in biological research.

What really novelty in Motor Invariant Theory is the method for adaption motion. Given the basic attractors as start point for motion planning, the following question is how to tweak the dynamic to guide motion according to purpose. During this process, stability must be maintained, energy cost must be minimized and the computation should cost not too much. But such constraints or performance requirement reflects little about control object. The fact is that motion are stable but varies greatly; people walk with different gaits on different situations. The traditional control idea of constrain the motion within a range of errors are not proper for motor control. Motor Invariant Theory propose that the stability property should be qualitative defined. In the geometrical term, the shape and position of the attractor does not matter, the control objective is to maintain the attractor attractive and current state within basin of attraction. Such idea is modelled by the mathematical language of topology. Maintains the attractor attractively without consideration the shape and position means maintain the topology. In fact, changing the attractor shape and position can be a powerful method for motor control. This control strategy maintains the qualitative property and provides a bigger space for potentially energy efficient and computational efficient methods.

Two methods are developed following this principle. The first idea is entrainment. This idea applies to almost all the periodic system. For entrainment systems, the periodic behaviour will be enhance oscillation and reject perturbation. From the topological perspective, effects of entrainment include maintaining the topology of limit cycle attractor and enlarging the basin of attraction. The idea of entrainment is well supported by biological research, besides the anatomical evidence, the method is computational efficient.

Another method is based on symmetry and preserving law of mechanical system. A dynamic system tends to preserve many properties invariant during motion, like energy or momentum. Such system all the phase portrait to transformed in a special manner, which will cost little control energy.

Such transformations will form another important mathematical structure, the lie group.

It is easy to prove that lie group transformation will not alter the topology, thus maintains the qualitative stability of motion. More important, lie group transformation can be parameterized with a few parameters. By specifying such parameters, animators can specify the lie group transformation. This provides animator a direct method for modifying motion without worry about the topology and stability. As an example, three lie groups are developed, the offset group which will change the locator position, which mean change the direction of motion; the time scaling group which will modify the speed of motion, and also the energy scaling group which will modify the energy of motion. Equip with such tools, given a motion primitive, animators are allowed to modify the position, speed and amplitude of motion, without worry about the stability. More importantly, this research found that for rigid body systems, control input of each group element has a close form formula for computation, making transformation control method computational efficient. Such an idea is also supported by biological research, which has found the motion trajectory does have transformation invariant property.

Because Entrainment and Lie Group transformation are based on the topology invariant principles, these two ideas can cooperate

Such operations will change the shape and location of the locator, results many types of variation in motion, if the basin of attraction is modified to capture the current state, the motion will be stable and maintained, however, we can also deliberately to change the shape and position of the current locator avoid capturing current state, then motion will diverge, and finally converge to a different attractor. An immediate application is generate motion failure in a controlled manner, which will be useful in many situations, more importantly, we can make also tweak a neighbour attractor to capture current stable, this will generate stable motion primitive transition.

Such methods have been applied for various mechanical and motion control application.

The bouncing ball example shows a simple example of forming attractive limit cycle and altering the shape of attractor, in the process the bouncing height is maintained and can be justified against many perturbations. Another example is the bipedal walking. Although bipedal walking seems difficult, bipedal walking can happens naturally and there exists a limit cycle. By entrainment method, the limit cycle is enhanced and the basin of attraction is enlarged. This make the passive walking more stable and generate different gaits with different body structure and environment condition. With lie group operator applied, the passive walker capable walking on different terrains (offset action) with Different Speed (time scaling) or different step size (energy scaling). For the balancing example, entrainment will turn the dynamic system attractive and group operators will adjust the size of basin of attraction and the time needed to stabilize. Also the transitional motion of walking and balance can be synthesized with energy efficient method of little control effort.

Such motion results are compared with real life data. The simulation results comply with the real life experiment results. For the question how animals achieve the computational efficiency, energy efficiency and stability against various perturbations, Motor Invariant Theory proposes a feasible answer. For animation researchers, motor invariant theory proposes a method generation adaptive natural looking motion in a computational efficient and reliable way.

But as a new theory, Motor Invariant Theory has unanswered questions. Finding the attractors in the high dimension dynamic system is not an easy task. At the end of the research, motor invariant theory proposes several methods to simplify the dynamic space to make the task of finding locators easier. We propose minor degree of freedom can be neglected; dynamic space can be reduced according to the symmetrical properties or exploring the similarity and time shift property in chain like structure. Such methods help to add more details for synthesized motion, like the rotation, body and arm swing motion. Also may extend the method to other application like fish swimming.

But this question is not answered completed in this research.

Nature seems outsmart us very far. Even we have learned a lot from nature, we still have lots to learn.

This work presents a novel method for synthesizing character motions dynamically following the biological principle.

For Animation, it provides a computational efficient method for adaptive motion synthesis.

However, the new animation technique is not the only object; the underlying new perspective of biological motor control may be of more value.

The research starts with a careful comparison of biological animals and artificial machines.

The discovery is that although artificial systems can move in a manner similar to biological animals, the control principles are very different.

This is because such artificial control methods cannot be scaled up to the complexity of biological systems.

Also the robust stability, energy efficiency and computation constraints imply that the biological systems must have adopted different control approaches.

This research takes this inspiring finding as the key research question.

We think that the control difference may be the crucial reason for the artefacts of current CMS methods and also the key obstacle in CMS is not the lack of algorithms or powerful computers, it is the misunderstanding of the biological motor control system. To improve CMS, we need a better control idea.

This thesis propose the new motor invariant theory, which is a very different idea about biological motor control.

Based on the finding in biological research, MoIT proposes that the questions of control and planning motion trajectory can be transformed into the questions of the manipulating the topology and symmetry of natural dynamic system. This new viewpoint provides a new but powerful way to understand natural motion and control. Since natural dynamics is governed by the body and environment, the new theory captures the characteristics of in the intensive body-environment interactions from the beginning. Unlike the other theory that contradicts with biological finding, the new theory complies with the biological facts and is informative in details.

In theory, it provides valuable information to understand the moving animal; in practise, it provide a method that is simple and computational efficient.

With this theory, motions that are unstable and challenging from traditional perspective can be synthesized with simple control. The bipedal walking example in chapter 6 shows that methods based on the new theory generates stable, adaptive, efficient and natural looking motion. In Chapter 7, we shows even the transitional motion can be physically synthesized adaptively by methods of the same framework.

However, currently the new theory is far from sound and mature. The principle can be scaled to system of any complexity, for attractor and the symmetry property of natural dynamics are common.

However, since topology and symmetry are recent developments in mathematics, tools for analysing topology and symmetry are not sufficiently powerful.

Except for certain cases, analyzing the topology or symmetry of general dynamic systems remains a difficult mathematical problem. Chapter 8 provides some idea of based on approximation or working around, but more research work is needed.

## 9.2 Further Work

Motor Invariant Theory is not an improvement of existing CMS techniques, it is a different paradigm. This thesis does not explore the full implication and potential of the new born theory. There are rooms for improvement, new techniques to developed and even new questions to be answered. This section summarizes several potential topics that may interest computer graphic or biological research communities.

## 9.2.1 Stable Templates For Motion Primitives

Research in this thesis starts from unstable system, stability is enhanced by adding control effort. Motor control is a complex task. In many cases, it is impossible to model all the control efforts that turn an unstable system into stable ones.

An alternative method is to start from a stable system and modify its shape to match the observation. Such methods may lose the details of motion but provide better stability and controllability. For games or film production, this idea may be important; animator requires controllability and stability over physical realistic. For characters performance acrobat, the characters must not fall even dynamic system is unstable in nature.

## 9.2.2 More Types Of Symmetry

More type of symmetry will generate more type of transformation that can be applied to the adapt motion. All the group actions adopted in this research are linear transformation group, which are easy to compute. But the types of transformation are very limited. Exploring more types of symmetry may provide a different adaptation schemes and may expand the theory to different motion primitives.

• Discrete Symmetry Properties Bipedal motions are synthesized in this research, an interesting idea is whether four or more legs motions can be built based on the bipedal walking strategy.

This can be done by exploring another type of symmetry: discrete symmetry.

For the house hound, the hind leg and font leg will move in synchronization or in anti-phase.

• Non-linear Symmetry from Structural Parameter Turning Non-linear symmetry preserving transformation will generate more type of adaptation. Since non-linear transformation is more difficult to find, it remains questionable how a biological system perceives it and applies it for motion adaptation. However non-linear transformation is suitable for modelling the transformation resulting from tweaking system parameters. For the idea of structural stability we know the results of tweaking system parameters are equivalent to having a one-one mapping transformation. Further research result from non-linear transformation may potentially completely solve the motion re-targeting problem

• Symmetry of Partial Differential System

All the methods developed are for ordinary differential equations, which is good enough for rigid body dynamics. In fact the topological property and symmetrical property also apply to partial differential equations. A famous example in physics is the Lorenz transformation group and Maxwell equation.

Symmetries of partial differential equations are important for they may extend the control strategy to control the motion elastic body or locomotion in fluid.

Such motion are more expensive are little addressed by current CMS methods.

To exploring more types of symmetry, reformulating the form of equations may ease the task. Current dynamic equations are based a fix coordinates frame. It is helpful to formulate the equations in the coordinate free manner or in the local frame.

## 9.2.3 Transform the Motion Capture Data

For computer animation, even methods for simulation high dimensional characters are proposed. It may be impractical to synthesize all types of motions by procedure method. An alternative method is to use dynamic simulation to modify motion capture data, which is well addressed in many researches in computer graphic community

Based on the idea of topological equivalence, motion primitive of different persons or motions of different situations should have the property of topological equivalence. In state space, there should exist a one to one mapping transformation function. Motion

Data can be converted into the state space and transformed by one-one mapping.

We can use the low dimensional model to find the one to one mapping relationship, which is applied to transform the high dimensional motion capture data. Potentially, this method may retain the motion details and involves little computational work.

## 9.2.4 Muscle Actuation

In the thesis, control effort is applied directly to each DOFof the mechanical system.

In biological research, this process is not so direct. Neural system generates some chemicals which affects the material properties of muscles. And force is generated　as an indirect side effect.

The question muscle actuation is untouched in this research, but with a second thought, MoIT also provides an alternative idea of muscle action. Transformation is the reason for applying control effort, the actuation of muscles can be calculated directly from the transformation, without caring about the force generated. From this perspective, muscle actuation can be easier than calculating the forces.

For the simple mass spring system, offset can be implemented by changing the rest length parameter d. Speed action can be implemented by changing the stiffness K. and energy scaling can be achieved by adjusting the stiffness K and then restoring it.

The reason is transformation can be achieved by two methods. Either control effort or by changing the system parameters.

For biological system, the method of changing parameters may be better for it will help motor control system get rid of the necessary feedback and computation. In fact most of control effort in the thesis is potential energy shaping, which only involves modifying the potential energy. If muscles are modelled as spring, then potential energy shaping can also be achieved through modifying spring parameters.

The complex muscle structure may provide a mechanism for fine turning the deformation of the phase portrait and the attractor can be changed into any possible shape. This idea may propose a conjecture for further biological research. For graphic research, incorporating muscles in this manner will have no effects on motion synthesis or computational work. The potential benefit is that the parameters of muscles can affect the skin deformation.

## 9.2.5 Perception based Dynamics

Motion perception is a high level capacity; it is based upon our object recognition ability and our dynamic reasoning ability. And many physiological questions in computer graphics may finally conclude with the recognition and perception research in neural science. The introduction of a motion synthesis method also touches the question of dynamic motion perception and encoding problem in intelligence. The topological equivalence and symmetry may also provide an understanding of the perception problem.

Based on the idea of topology equivalence, neural system may not need to encode the details of dynamic system; neural system can form an analogous dynamic system in our brain that is analogy to the real dynamics. Such model will lack the details accuracy, but get the qualitative properties right.

Based on the idea of symmetry, neural system may store some experience and the symmetrical property of dynamics in memory. Our brain may verify dynamics by transforming our experience to match observation.

We are still not sure which method is better, but both of methods are more practical for our brain than forming a symbolic equation solving the differential equations numerically. Maybe a new dynamic simulator can be designed to test this hypothesis.

Dynamic simulator can be build upon the topology and the symmetry property.

Animator can specify animation by specify its attractor and the transformation being applied. If the hypothesis is true, even the method will generate physically inaccurate results, audience will not notice it.