Chapter 9 CONCLUSION AND FURTHER WORK

# 9.1 Conclusion

Physics based Methods for synthesizing character animation have attracted lots of research interests in recent 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 the inverse dynamic problems are very challenging. Optimization or Data Driven based methods 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, and in fact attracts even more researchers beyond the computer graphics 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 motions than visionary properties that mainly are concerned by graphic researchers. They have identified the limited neural activity, stability and energy efficiency of motor control.

The current idea from biology science and robotic engineering experience rejects the popular 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. The inspiration from biology and robotic research is that the complexity of body dynamic may have a good reason. The complexity of the body dynamics is not to challenge the neural control system, on the contrary, the complexity reflects the sophistication of natural design. A sophisticate mechanical system may ease the control difficulties of many daily motion tasks. The new idea is that in fact most of the motion problems have already been solved by the nature, the evolution has equipped animals with very handy mechanical apparatus, so that many motion tasks can be accomplished without any effort. To meet the special purpose, animals only need to modify the basic motion behaviours in a brilliant manner.

These ideas inspired this research, animation methods are developed with a consideration of the biological facts. The belief is that if our animation method follows 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.

More valuable results arise from this researching process. To develop simulation programs, intuitive biological ideas are put to test for their computational efficiency and logical soundness. As a consequence, new mathematical interpretation and algorithms are proposed in this research. The new idea proposes more detail information in the motor control process. These new ideas are summarized as the Motor Invariant Theory. The new theory is more detailed and accurate compared with current biological ideas, and is applicable to control real robotics. If it can be approved by further biological research and experiment, this theory may have significant meaning.

Motor Invariant Theory is composed of several interconnecting ideas. The theory unifies these ideas in a very different perspective of dynamics. The traditional force -motion perspective is not insightful for understanding natural dynamic, because it provides little information about stability and energy efficiency of motion.

Motor Invariant Theory adopted the geometrical perspective. The concept of phase space is introduced and the dynamic system is transformed into a geometry structure: the phase portrait. After this transformation, motion dynamics can be studied 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 motor control. Because attractors promise stability, energy efficiency, they will greatly reduce control difficulties.

This idea has support from biological research. The idea of organized motions in blocks is proposed as the motion primitive hypothesise. And the idea of utilizing attractors has been proposed by the equilibrium point hypothesis. Such idea may be new for graphic researchers, but the principles are long established in biological research.

The novelty of Motor Invariant Theory is the idea for the adaption mechanism. Given the attractors as the starting point for motion planning, the following question is how the neural control system tweaks the dynamic to satisfy animals’ purposes. During this process, the challenge is that the stability must be maintained, the energy cost must be minimized and the computation should not last long. Optimization based methods are not suitable. Also the tracking controllers are not proper for motor control. Because motions vary greatly; people walk with different gaits on different situations. The idea of local stability control that constrains the motion within a small error range from the reference will make motion stereotype looking. Motor Invariant Theory proposes that the stability property should be controlled qualitatively. Large deviations from the reference should be allowed while stability is controlled. In the geometrical perspective, this means the shape and position of the attractor does not matter, the controller only needs to maintain the attractor attractive and the current state within the 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 motor invariant theory, changing shape and position of attractors is not only allowed but utilized as a powerful tool. The idea of changing the shape and position of the attractors not only generate adaptive motions, but also stable and efficient in energy and computation

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 enhanced and perturbations are rejected. From the geometrical perspective, the entrainment will maintain the topology of limit cycle and enlarging the basin of attraction. In addition, the idea of entrainment is well supported by biological research. Also the method is computational efficient.

Another method is based on symmetry and preserving law of mechanical systems. Natural dynamic systems tend to preserve many properties during motion, like energy or momentum. Transforming motions in the directions that preserve such invariant properties will modify motions energy efficiently.

Such transformation actions form another important mathematical structure, the lie group.

It is easy to prove that a lie group transformation will not alter the topology, thus the stability of transformed motions is guaranteed. This provides animators a direct method for modifying the motion without worry about stability. Also this method is easy to use. For lie group transformation can be parameterized with a few parameters. Animators can modify motions by specifying very a few parameters of lie group, instead of each \dof of the character. As examples, three lie groups are developed, the offset group which will change the locator position, which changes 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. With such tools, given a motion primitive, animators are allowed to modify the position, speed and amplitude of motion, without worry about the stability. As for the computation cost, this research found that for rigid body systems, control input of each group element has a close form formula, which is trivial to compute. The idea of Lie Group is also supported by biological research, which found the fact that the motion trajectory does have many transformation invariant properties.

Because the cpg entrainment and Lie Group transformation are based on the topology invariant principles, these two controllers can cooperate.

Such operations will change the shape and location of the locator, results in many types of variations in motion. If the basin of attraction is modified to capture the current state, the current motion primitive can be maintained. However, there are also important applications by change the shape and position of the locator to avoid current state. As a result, the motion will diverge, and finally converge to a different attractor. An immediate application is to generate motion failure, which will be useful in many situations. The more important application is in motion transition. We can tweak the neighbour attractor to capture current state, this will generate stable transitional motion. This shows how motor invariant theory can be easily extended to explain more natural motion effects.

Such methods have been applied to control various mechanical systems and characters. The bouncing ball example shows how the entrainment forms attractive limit cycle and how group action changes the shape. In this process the bouncing height is maintained and can be justified against many perturbations. Another example is the bipedal walking. Although bipedal walking seems difficult to control, it can happen naturally because there exists a limit cycle. By the entrainment method, the periodic behaviour is enhanced and the basin of attraction is enlarged. This makes the passive walking more stable. This qualitative control approach can generate different gaits with different body structures and environment conditions. When lie group actions are applied, the passive walker is capable of walking on different terrains (offset action), at different speed (time scaling) or with different step size (energy scaling). For the balancing motion primitive, 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 an energy efficient method of little control effort.

Such simulation results are compared with real life data; and they comply the observed facts.

As a conclusion, 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 that generates adaptive and natural looking motions in a computational efficient and reliable way.

But as a new theory, there are still many unanswered questions. Finding the attractors in the high dimension dynamic system is not an easy task. At the end of the research, several methods are proposed to simplify the dynamic space to make the task of finding locators easier. We propose degrees of freedom with minor motions can be neglected; dynamic space can be reduced according to the symmetrical properties or exploring the similarity and time shift property in many mechanical structures. Such methods help to add more details for synthesized motion, like the rotation, body and arm swing motion. Also the method can be extended for more applications like the crowd and swimming simulation. But this question is not answered completed in this research.

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

## 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, techniques to develop and new questions to answer. This section lists several potential topics that may interest computer graphics or biological research communities.

## 9.2.1 Stable Templates For Motion Primitives

Research in this thesis starts from the unstable systems, stability is enhanced by many controllers. However, the biological motor control system is very complex. Maybe it is impossible to model all the control strategy involved in biological system to turn the unstable system into a robust one.

An alternative method is to start from a system with stable topology and modify its shape to match the observation. Such methods may results artefacts in details but it provides better stability and controllability. For games or film production, this method may be more efficient and easy to use, because animators require controllability and stability over physical reality. For characters performancing acrobats, they must not fall even dynamic system is unstable in nature.

## 9.2.2 More Types Of Symmetry

More types of symmetry will provide more transformation groups that generate more adaptations. The group actions examined in this research are linear, which are easy to compute. But the number of types is very limited. Exploring more types of symmetry will not only provide more adaptation schemes but also expand the theory to control 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.