Adaptive Motion Synthesis Based on Invariant Motion Signature

In this paper, we propose an new approach for synthesis physics based character motion.

This approach produces energy efficient motion while involves very little computational cost.

It is also friendlier than original physical based method.

We propose that motion is made up of many motion primitive, motion adaptation is achieved through a kind of group action on the motion primitive. Some properties of motion primitive are kept during motion adaptation.

This idea can be modelled with Structural Stability and Lie Group Symmetry.

Via our method, the original variation programming methods are simplified as an element searching problem on the Lie Group Manifold.

Thus computational cost is greatly reduced.

As an Example, we show an efficient and realistic locomotion controller.

# Introduction

Human beings are very sensitive to motions.

From the variety in motion details, humans can infer the changes in mental states, health conditions or even the surrounding environment.

This makes Character Motion Synthesis (CMS) a challenging task.

In industry, high quality motions are still majorly generated by animators' manual work.

Because of the complicate structures of characters, a large number of joints need animator to tweak and setting key frames.

To make things worse, it is very difficult to reuse these motion data.

When the environment or the character changed, the animators have to manually design new motions.

In the past two decades, lots of work has been published to achieve the target of generating realistic character motions.

Many researchers are trying to generate lifelike motions automatically by simulating the dynamics of body, environment and the neural control system.

However since each virtual character is full of redundant degree of freedom, it not only increases the computational load, but also makes the solution nondeterministic.

In Biology, researchers found out some important features for the motions of living creatures:

ADAPTIVE

Natural motions are adaptive to the changes in the environment or body conditions. For example, a human being can easily adjust its walking motion according to different terrains.

AGILE

The reaction of human and most animals are very fast. Even in a very complicated changing environment, human can change their motions in real time. However from the biology research, the simple functionality and slow processing speed of human neural system make it almost impossible to solve complex motion control problem in a real time.

ENERGY EFFICIENT

According to Darwin's Theory of Evolution, a natural motion should be energy efficient. Live creatures spent far less energy than we expected. An example is that the energy consumed by human walking is only 10% of that for a robot of the same scale.

Current Researches have not answered above questions feasibly. The above three important features are very difficult to achieve by current CMS methods.

MOTION PERCEPTION

Perhaps the one of the most important we neglected in in CMS research is \textbf{motion perception}.

For compute animation application, animations don't have to be physically corrected as long as audience don't notice.

An interesting question is how a human can find the artefacts in motion instinct, when there is no time for computing the physics reality.

An alternative idea is motion perception is based on some key characteristics of motion. These key features are kept unchanged during motion adaptation, and are called motion signature.

Contribution

In our research, based on the new theory in neural control research, we developed a novel motion control and computation framework.

The biological idea is neural system don't have to synthesis motion from group up.

Motion is made up of many motion primitives; neural control system modifies the basic motion primitive to form new motion.

During motion adaptation, some key properties of motion primitives are kept unchanged.

Such invariable characteristics are called motion signature.

In our research, we mainly keep two motion signatures.

The first signature of motion is the topology structure of motion dynamics.

The topological structure will provide the structural stability.

This signature provides the basic stability of motion and basic adaptation power for motion.

Another signature is Lie Group Symmetry.

Lie Group Symmetry provides a mechanism for finely refine motion details.

For motion, it provides a method for meet motion constraints.

For animation, it provides a mechanism for refine motion details.

Our methods is computational efficient.

# Related Work

Motion Synthesis is a topic involves much research area, like biology, neural science and computer graphics.

It is impossible to include all the research work on motion synthesis.

In this part, we will only talk about the mainstream method in computer graphics and research related to our search from other research community.

## Dynamic Motion Synthesis and Control

Dynamic Motion Synthesis tries to synthesize character motion through physical simulation of the mechanic structure of character body which is usually modelled as a linked rigid body system \citep{Baraff1994,Mirtich1996,Stewart2000}.

Since many real physical properties are considered in the computation, the generated motion are normally physical feasible. However the most difficult task for those methods is to design a efficient control system to simulate the functionality of a real biological neural system.

Some early research applied classical control methods like PD controller \citep{Raibert1991} for locomotion.

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

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

However both the classical PD controller and Limit Circle Controller predefined motion trajectories and eliminated perturbations. This makes them not good at generating motion adaptation.

Because lots of degrees of freedom are involved in the whole body simulation, in most cases, motion solutions are not unique.

Many optimization methods have been applied to choose the ``best'' motion. For dynamic methods, a reasonable choice is to minimize the energy cost~$V$, such that

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\textbf{V}=\int\_{t0}^{t1}F\_{a}(x)^2dt

\]

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}, and serve as the foundation for many modern CMS research. \citet{Jain2009} provides an example for locomotion; \citet{BalanceControl} find a method for balance maintaining movement. \citet{Liu2009} proposed a method for object manipulating animation.

The Spacetime method may modify the motion trajectory and in nature it solve the problem through variational optimization. However it faces several key problem.\\

\subsubsection\*{Efficiency}

In many cases, it will take very long time to find the "best" solution and there is no guarantee the optimal solution can be achieved. And for complex body structures the computation will takes prohibitive long time \citep{Anderson2001}. Optimization techniques like time window and multi-grid techniques are proposed by \citet{Cohen1992} and \citet{Liu1994}. Very a few research \citep{Popovi'c1999} proposed Spacetime Constraint for full body dynamic animation.\\

\subsubsection\*{Sensitive and Overspecific}

Current numeric methods are very sensitive to model accuracy and initial conditions. Precise model for both the environment and body have to be prebuilt. \citet{Liu2005} points out that spacetime constraint methods only suit high energy motions like jumping and running; for low energy motion tasks like walking the result doesn't looks nature. This is mainly because the muscle effects are neglected. Motions like heart beating, breathing, or motions of other animals such as the swimming of fish and jellyfish, flying of birds have not been synthesized with dynamic methods for the lack of a feasible dynamic model.

## Biological Research

In biological research, motor control is an age old problem full of paradoxes.

Motor control in nature is a complex process involving many chemical, electrical and mechanical effects.

So most of Dynamic motion synthesis methods tries to simulate the reality through very complicated computation.

However this is very opposite to the characteristics of the neural systems of real creatures \citep{Glynn2003}: \\

\subsubsection\*{Time Delay}

Neural signal transmitting speed is very slow; and there is a long delay between neural signal firing and force generation in muscles.\\

\subsubsection\*{Noisy}

Besides the delay and low speed transition, the neural signals are also noisy. The body structure and environment are also nonlinear, noisy and time varying. \\

\subsubsection\*{Limited Activity}

Current research evidences and common life experience show that motor control involves little control effort. Many experiments show motion can happen even without brain input.

Despite the complexity of body structures and environment, the natural motor control strategy seems relatively simple involving very little computational work.

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

There are many experimental researches in robotics and biomechanics succeeded in controlling some motion with very simple strategy\citep{nishikawa2007neuromechanics}.

\textbf{Uncontrolled Manifold Hypothesis} method even proposed that some DOFs are not controlled and freely influenced by the environment \citep{latash2008neurophysiological}.

The\textbf{Equilibrium Point Hypothesis} method suggests that what the neural systems controls is not trajectory, but the final position.

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

Impedance Control proposed the extra DOFs provide a way to control the stability and admittance of final postion according to the motion purpose.

\textbf{Morphological Computation Theory} \citep{nishikawa2007neuromechanics,Pfeifer2005} thinks both the body structure and the environment play a crucial role in motor control, basic motion patterns are generated by body and environment, the neural systems only maintains or tweaks such motion patterns.

The biological ideas provide space for an efficient motion adaptation, but the theory are incomplete and mainly for explaining experiment results. There is a big knowledge gap to turn it into a sound control theory.

## Differential Invariants

The mathematical techniques of our method is greatly influenced by the idea of Erlangen program that initialized by Kelin. That retreat the geometry from group action and invariant paradigm.

I(G(x))=I(x)

For physical motion synthesis, motion is often modelled as differential system.

Topology and Lie Group Symmetry capture the global and local invariants, they played a key role in mechanical and mathematical research.

For animation research, recently there is application of Lie Group methods in mechanical simulation like vehical simulation.

# Motion Primitive and Invariant

In our framework, the complex human motion is made of many motion primitives.

During motion Adaptation, neural system modifies the basic motion primitive to synthesis new motion. The adaptation is modelled as group action and motion primitives are defined by the differential invariants.

The Differential Invariants investigated in our research is the Topological Structure and Lie Group Symmetry.

Topology Structure determines the motion stability and provides the basic ability for structural adaptation. Lie Group Symmetry is applied for modifying motion details that allow animators to specify motions to meet their special demands.

## Topology and Qualitative Motion Control

In our motion control framework, we only care about the some qualitative of motion.

One key qualitative properties of motion is the final motion result,from the geometrical viewport, this mean only the

basically motion can be separated into two group.

1 periodic motion

Some motion show pepetive pattern, from geometrical viewport, on the phaseplane, the attractor of curve form the shape of a circle.

2 discrete motion

Another idea is

## Motion Control based On Lie Group Symmetry

### Symmetry of Motion

An idea in solving differential equation and mechanical control is based on the idea of Lie Group And Symmetry.

Define Invariant of G, if I(x)=I(G(x)), the I is an invariant function of G.

In physical based system, motion is the solution to the corresponding differential equations

if $x(t)$ is the solution of a differential equation $\dot{x}=F(x)$

if for a group y=G(x); if y satisfy the equation $\dot(y)=F(y)$

then y(t)=G(x(t)) is also a solution of the the function $\dot{x}=F(x)$.

Then the group G transform the solution x(t) into another solution y(t);

Thus Give the symmetry of differential and corresponding Lie Group G, we can transform a motion x to and Motion Space X where g(x) \in X.

For physiccally based system,

State Space is belongs to q is (x,\dot{x})

The motion of of a mechanically system is determined by the lagrange $L$ and corresponding Lagrange euler equation.

L=K-V

K is the kinetical energy is a function of (\dot{x}), V is the potential energy, which is a function of

in our framework, the basic motion pattern is given, if we want to keep the symmetry motion, than the control problem can be simplified as an group element finding problem.

simpilifed find the corresponding group element $g$.

In our research, we separate the group space of G in two SubGroup.

The Transform Group, which don’t modify the Tangen Space and Group Action which don’t Modify the State Space.

### Space Transform

G\_T(r)(X)=(X+r,Tx)

Space Transform motion is used to Transform a into a Specifiy Direction in Space.

I\_GT=X-X;

Usually, for rigid body dynamic system, kinematic energy is in the form of \dot{X}MX,

M is mass inetia Matrix, which is usally a function of I\_G(X), thus we have the following Thereom.

Thereom K is a function of I(x) and Ta, then the Space Transformation will not modify the Kinematic Energy.

### Time Scaling

Time Scaling are used to modify the motion speed.

G\_s(a)\*T=aT.

G\_s(a)(x,dot(x))=(x,1/aDot(x))

Thereom Time Scalling will increase the Kinematic Energy while Keep the Protential Energy, and scale the kinematic Energy of a factor of (1/a)^2

### Controlled Symmetry And Energy Shaping

In Motion Control, usually the original motion X, and the desired motion Y are known. But the group action g may not satisfy the symmetry of the differential equation.

This forced us to modify the differential equation to add a unknown element, in motor control, this is where the control effort is applied.

We modify the differential equation to include control force u.

D((dL/dq))/dt+dL/dq=u

We can modify u to make the desired symmetry statisfied.

If motion is energy efficient, then the controlled system should be natual looking.

Then we have

L(G(q))-u=L(x)

Space Transform G\_t .

K is persperved, than u=G(v)-v

For Time Scaling K is scalling by a factor 1/a;

## A simple Example