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1 Motion modeling and computation

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In this part, we will examine the main types of models to represent motions in the aim of positioning them in the action-vision chain and of analyzing their strengths and weaknesses from an enactive point of view.

During the first phases of the Computer Graphics development, until the 80's, the main feature brought by computer animation, compared to the conventional cinematographic approach, was the automation of interpolation processes between key-frames [Lasseter 1987]. In the middle of 80's, with the apparition of deformation and transformation models, the computer models for motion synthesis followed various directions and the research in computer modeling and synthesis experienced a new boom.
Up to now, computer models for motion synthesis has been usually classified in three main categories :

• Phenomenological models of motion by means of cinematic evolution functions
• Generative models of motion by means of physically-based models
• Generative models of motion by means of behavioral models of artificial life and artificial intelligence.

In the following, we present the properties of each of this type of models, positioning them with the shape modeling.

1.1 Phenomenological models of motion

1.1.1 Principle

Key-frames and interpolation methods (including morphing techniques) are related to a phenomenological representation of the motion. These methods have been improved by cinematic representation in which the evolution of morphological (positions, shapes) or visual (color, intensity) parameters is represented by temporal evolution functions where the time is an explicit variable: Motion = f(t).
Such representation supposes that the morphological and visual parameters are predefined and their evolution is applied on them. It can be considered as a mapping of motion on predefined object. Then, the methodology consists in :
• Modeling the 3D non evolving object by means of geometrical modeling (whatever the representation is - as described in the previous paragraph "3D modeling). In these representations, the time is absent.
• Applying evolution on the geometry of visual parameters of such models.

1.1.2 Types of phenomenological models

There are three techniques in the phenomenological approach of motion:
• Key-framing and morphing
• Explicit interactive evolution functions
• Kinematics models

• Key-framing and morphing
Assuming that particular states are relevant in a continuous motion, key-framing and morphing technique is based on the idea that only particular states are relevant in a continuous motion. Thus, the modeling process consists in establishing the definition of such "key-frames" and in reconstructing the continuous motion by interpolation methods. In the 80's, methods to automatically generate families of key-frames from existing motions are developed, mainly for the human motions from biomechanical information. A lot of interpolation methods have been developed. Mainly, they are based on mathematical functions (linear, spline and Beziers functions, etc.) as spline functions and they take into account various criteria such as:

- the presence of singularities of the complex motion for rendering smoothness, transients, breaking points, etc.,
- the localization of the interpolation process between the control points,
- the control of the derivatives in order to generate motion families (proximity, tension, etc),
- the control of the velocity variation including effects like anticipation, stretching, squeezing,
- the smoothing in specific points (starting and end points), etc. [Burtnik 1976] [Steketee 1985] [Reeves 1981] [Friedrich 1998].

• Explicit interactive evolution functions:
The motion applied to a 3D shape can be defined explicitly by evolution functions, mathematically defined [Coquillart 1990] [Coquillart 1991] [Lamousin 1994] [Frish 2002] [Milliron 2002] or provided by sensors (mouse, sticks, motion capture devices). Even they can be controlled, the mathematical functions offer a limited set of expressive motions, with too much regularities. Signals provided by sensor inputs that acquire human gestures corresponding to real motions do not have this type of limitations.
Motion captures are techniques widely used to profile free-motions. Nevertheless, the signals provided by such motion sensors input have to be processed by signals filtering in order to obtain a sufficient signal to noise ratio, respectively by applying extraction features processes in order to obtain data usable for the motion design. The signals provided by sensors are generally noisy and characterized by a lack of clear information. They have to be improved by signals filtering and reconstruction processes.
In terms of low-level control, this type of representation corresponds directly to devices that are pure sensors (non-retroactive sensors).
In term of high-level control, the signals representing the motion have usually the form provided by the sensors, for example position sensors. Usually, a high-level animation control needs to transform these signals in others, like: velocities (t), direction changes (t), etc…

• Kinematics models
Kinematics representations of motion are generated by mathematical descriptions of the object kinematics. These types of techniques are well adapted to the representation of the displacement of solid, rigid or articulated rigid objects.
The main limitations of such approaches are situated in the representation of complex motions like:

- Complex dynamic non-linear features (fractures, states changing, etc.),
- Motions that are highly correlated and interdependent, for example deformations allowing the representations of the non-penetration during collisions, the temporal relation between displacements and shape deformation, the coupling between two deformations,
- Evolving scenes in which there is a huge quantity of different motions, as in collective interactive phenomena

In term of control, there are two ways to model an expected motion: direct and inverse kinematics. In direct kinematics, temporal evolutions are calculated by mathematical functions in which time is explicit: $\Delta X(t) = J\,\Delta Q(t)$, Jacobian matrix $J_{ij}=dX_i/dQ_j$. If the action is designed in term of task to be performed (for example to reach a target) and not in term of movement performance, the modeling process consists in defining targets and in calculating motions by means of inverse kinematic methods. These types of methods are related to the modeling of constrained motions.

1.1.3 Main properties from an enactive point of view

The two main properties of such phenomenological models of motion, related to the action-vision fusion and seen from an enactive point of view are:

1. Such phenomenological representations are well adapted to the free-hand control. We call free-hand control, the control of motion through human gestures that are not constrained by the object manipulation. This kind of control corresponds to the “pure semiotic action” in the Cadoz’s typology of gestures [Cadoz 1994, 2000] and they may be conveyed by non-retroactive transducers as pure sensors. These sensors work

through extensive variables [Luciani 2004], as displacements, positions, velocities, that follow the principle "observable variables". At a first glance, they seem to be well adapted to the direct hand manipulation. The "hand-eye" chain, underlaid by such representations is a direct chain: from extensive variables given by gestures to geometrical computations and representations, which process also extensive variables (positions, shapes, etc.). All the processed data are extensive variables, i.e. of the same nature.

2. The motion is applied on a shape. This means that the representation of the world is a geometrically - based representation. The geometrical features are "given", they only have to be modeled. This means that the approach from an enactive point of view differs (1) from the ecological cognitive approaches for which the space is built from psycho-cognitive experiences and (2) from the emergent dynamic approaches for which the shapes derive from the motion. In such phenomenological approaches, the spatial properties (geometrical shapes) of the space are predetermined and precede motion. In ecological cognitive approaches, shapes are built. From dynamics approaches, shapes are not predetermined but they emerge from movements. Only the infinitely rigid objects are compatible with such phenomenological approaches.

1.2 Generative models of motion

The strength of phenomenological models consists in the fact that they correspond to an explicit description of possible observed motions and performances, to be phenomenological. They are underled by an analysis-synthesis method. Theoretically, any motion can be represented by such methods. Nevertheless, their complexity increase dramatically in representation of high level qualities as "softness", "hardness", "rhythm changes", "dynamic complex correlations of complex shapes motions", "emergent non predictable evolutions.

This led to the development of generative models of motion. Here generative means processes in which the time is implicit and the calculation process produces families of evolution functions according to the parameters of the generative processes. There are two types of generative models:

- The physically-based models, modeling the dynamics.
- The agent based models, developed in artificial intelligence and artificial life.

1.2.1 Physically-based models

1.2.1.1 Principle

Physically-based modeling implements dynamics. They are basically motion generative due to the fact that Dynamics computes the kinematics of motions. In ancient Greek, "Dynamo" means forces, and "Kinema" means movement. Dynamics is based on the use of intermediate intensive variable – namely the force – to compute co-evolution of extensive variables. The intensive variable, with its native action-reaction principle, represents the mutual influences between two observed extensive variables. In computer simulation, the processes are:

1. a couple of extensive variables produce intensive variable through interaction laws,
2. intensive variables produce extensive variables through behavioral rules,
3. extensive variables are used to display motion.

In computer animation, physically-based models have been used, in a first time, as computational method to solve minima problems as the penalty method in collisions algorithms, and more generally, as a constrain solver used locally in kinematics (direct and inverse) approaches. Afterwards, they have been used to synthesize natural evolving phenomena. A lot of works were devoted to the simulation of realistic evolving natural phenomena by implementing dedicated physics models (calculation of Navier-Stokes equation for turbulences, heat equations, tridimensionnal elasticity, etc.). They have been rarely used as a generic method to model dynamics behaviors. More recently, physically-based particle methods [Greespan 1973, 1997] [Luciani 1991] have been developed, allowing the modeling of a huge variety of dynamic effects and motions, with minimal models easy to compute.

1.2.1.2 Types of models

There are three main types of physically-based models:
• Continuous models
• Mesh-based discrete models
• Particle-based discrete models

<u>Continuous models</u>

The phenomenon (for example, deformation of an object) is represented in a continuous formulation. Each model corresponds to a specific phenomenon: rigid and flexible objects [Terzopoulos 1988a] [Terzopoulos 1988b] [Baraf 1992] [Terzopoulos 1993], Metaxas 1996], tridimensionnal elasticity, Navier-Stokes equation for turbulent fluids, matter transport for granular material, friction models [Baraf 1991] etc. Thus, such differential partial equations are solved according to various methods for : finite difference method, implicit and explicit resolution etc. These models are mainly “one-shot” models, able to produce highly realistic motion, but less reusable, and less easy to design and to manipulate.

<u>Mesh-based discrete models</u>

The most known method is basically the finite elements method (FEM), used to calculate the dynamic behaviors of objects. FEM was widely used in mechanics to compute deformations of compact mechanical bodies. It is also widely used to solve problems as variational problems in physics. This method is a geometrically-based physical one in the sense that the geometrical features (shape, volume) of the body are given and discretised in space by geometrical basic elements, constituting a mesh. The forces applied within the elements are contact and cohesive local forces representing the contiguity of the matter. A lot of works that use this type of method exist in the field of mechanics, that leads computer graphics researchers to use it. Since the shape is predefined and maintains its cohesion, this method provides complex deformation of complex body.
Another mesh-based methods are those used to simulate behaviors of continuous medium (fluids, gas, etc.), called lattice methods (Lattice Gas Method, etc.). They were rarely used in Computer Graphics. The reason is probably that computer graphics focuses mainly on object exhibiting a clear shape, even if this shape is deformable.

<u>Particle-based discrete models</u>

Particle-based models appear more recently in Computer Graphics. They were used since the beginning of computer calculations in physics, as in the Los Alamos laboratory to compute complex behaviors of turbulent fluids. There were stopped due to the low computation power of computers at that time. The exponential increasing of the computational power of computers renders newly attractive this approach. The usual understanding of this method, often named mass-spring, (physical objects being modeled by a set of punctual masses linked by elasticity) reveals that, in computer graphics, physical modeling is understood only as an implementation of the rules of physics, rather than as a generic method of modeling, at the

same level of abstraction that neural or cellular automata networks. Used in such way, its modeling power as well as its computational efficiency is obviously limited. As described by their founders [Greespan 1967, 1997] [Luciani 1991], physically-based particle modeling is a modeling concept based on the explicit duality of variables, extensive variables (EV) and intensive variables (IV) , and the basic action-reaction principle.
It allows to understand the physical modeling, not only as a representation of nature, but as an abstract representation system by which we describe algebraically the dynamic correlation between two (and further any number of) dynamic phenomena, whatever they are, this algebra being based on two dual variables: one (EV) describing the intrinsic evolution of the phenomenon from the influences (IV) of all the others phenomena, and one (IV) describing the mutual influence between each pair of them from the evolution of extensive variables (EV). All the rules that are involved to model a dynamical system are rules that links EV and IV. These rules can be called “physical rules”. We can notice that natural phenomena are obviously represented (modeled) in Physics (Mechanics, Electricity, etc.) by these types of abstract rules.

From this abstract point of view, a physically-based particles model is a network of dynamic automata, similar to the well-known Kirschoff’s network in Electricity, in which behavioral differential components producing extensive variables are linked by differential interaction components producing intensive variables. This type of network can be seen as a type of cellular automata calculating real states instead of logic states. Several works show that such methods are able to produce any types of motions: from displacements of rigid or articulated bodies [Nouiri 1994] [Chanclou 1995] [Chanclou 1996] [Jimenez 1993] to complex emergent dynamic phenomena (as crowd behaviors [Luciani 2003]), including all types of deformations, complex motions as chaotic or non-linear evolutions (avalanches, collapses, fractures, etc.) [Luciani 2000] and all the various states of the matter (fluids, gas, solid, pastes, etc.) [Luciani 1995b] [Luciani 1995a]

<u>Note : Direct and Inverse Dynamics</u>
In Computer Graphics, literature states frequently on direct and inverse dynamics. Direct dynamics calculates extensive variables as positions (variables to be displayed) from intensives variables as forces. Inverse dynamics calculates the intensive variables from extensive variables, and it is mainly used as a control process to calculate the forces to be applied to reach a given position. As physically-based models integrates the two stages and are controllable either by positions or by forces, we don’t examine here these two particular cases of computation as general method to produce motion.

1.2.2 <u>Behavioral models</u>
Models based on artificial intelligence or artificial life approaches are the second type of generative models used in computer motion modeling and synthesis. They were initially used to model mainly behaviors of living organisms. Similarly with physically-based models, they can be used as an abstract representation to models evolutions, whatever these evolutions are. Physically-based models are used to model physical phenomena but also the dynamics of non physical phenomena. Behavioral models are used to model autonomous evolutions, for living or non living beings. The complementarity between these two types of models has been well expressed by Newman and Comper [Newman 1990] in the case of living tissues modeling. They called the first type of model (physically-based model) “generic systems” and the second “genetic systems”. Generic mechanisms are defined as those physical processes that are broadly applicable to living and non-living systems, such as adhesion, surface tension and

gravitational effects, viscosity, phase separation, convection and reaction-diffusion coupling. They are contrasted with 'genetic' mechanisms, a term reserved for highly evolved, machine-like, bio-molecular processes. Generic mechanisms acting upon living tissues are capable of giving rise to morphogenetic rearrangements. Many morphogenetic and patterning effects are the inevitable outcome of recognized physical properties of tissues, and generic physical mechanisms that act on these properties are complementary to, and interdependent with genetic mechanisms. Major morphological reorganizations may arise by the action of generic physical mechanisms, that could be stabilized and refined by subsequent evolution of genetic mechanisms.

There are two major types of behavioral models: Genetic algorithms and Agent-based models. Genetic algorithms, as L-systems or cellular automata, aim to model developmental processes based on genetic evolutions. Agent –based models are mainly based on implementation of perception-decision-action processes, to model autonomous behaviors. In computer graphics they are widely used in modeling of living growing [Prusinkiewicz 1993, 1999, 2002] [Lindenmayer 1992], living behaviors, evolutionary processes, morphogenesis processes, autonomous behaviors [Sims 1991, 1992, 1994] [Musse 1999], and emergent cooperation between actors [Panatier 1998] [Heguy 2001] [Sanza 2000].

1.2.3 Main properties from an enactive point of view

Physically-based modeling

As said before, Computer Graphics was mainly oriented, during its first stages, in geometrical and light modeling and computing. The main features of scenes and objects that have been taken into account are morphological and visual features. Physically-based models introduced the physical properties of objects in virtual objects and scenes, with new variables as intensive variables (forces). In addition to their ability to produce easily higher quality in complex motions, the introduction of physically-based models cause two shifts, at the conceptual as well as at the pragmatic level:

• Firstly, they allow to introduce mechanical retroactive transducers for the gestural manipulation. In order to be felt, the matter has to be modeled and simulated. Geometrical models are not able to generate forces. The only case in which geometrical models can be used to generate force is to render an infinitely rigid shape by predetermined potential fields. Thus, physically-based modeling is the core component for retroactive action and the physical manipulation of virtual objects. The ergotic interaction [Cadoz 1994, 2000], that needs force feedback devices and force computation, i.e. physically-based modeling, has been the last to be introduced in computerized environments. From the enactive point of view, enactive interfaces cannot avoid such interaction, which plays a complementary role of pure epistemic-semiotic interaction loops between pure non retroactive action and vision (and audition).

• Secondly, up to now, the main stream in computer graphics and VR is devoted to geometrical modeling, the motion being mapped on predefined shapes. The shapes were represented only through their geometrical (no-matter) features, that are basically static representations. Physically-based modeling introduces the matter as a core component of object representation. The complementarity of the two parts (geometry and matter) of the objects modeling are not obvious to define and implement. Only physical models that are based on geometrical features, as meshes or lattices, allow a direct and compatible link with the geometrical representations of shapes. But, as we said, they are limited to continuous matter and they do not allow a wide use of non-continuous behaviors (collisions, fractures, manipulation of pastes or fluids, etc.). These types of physical objects cannot be avoid neither in VR systems nor in telemanipulation or telecommunications. In addition, physically-based models are able to produce more complex unformed and highly evolving shapes as in such complex behaviors, than those produced by pure geometrical modeling and kinematics.

-> Faced to the available computational power and its foreseen evolution, will these different processes, one focusing on the shape and the vision, another focusing on the matter, the motion and the manipulation, pragmatically compatible in enactive interfaces?
-> Faced to the underlying concepts – one focusing on the predetermined geometrical properties of space, another focusing of the dynamic construction of such properties – will there different concepts conceptually compatible in enactive interfaces?
-> What types of typology of tasks, can we define in which an optimal use of each of them could be designed and implemented?

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