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COMPUTATIONAL PHYSICS : A MODELER - SIMULATOR FOR ANIMATED PHYSICAL OBJECTS

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Abstract
Physical modeling for animation is now firmly established. The present aim is to design and build a structured and well-defined tool rather than merely specific algorithms to simulate physical knowledge.
We will first define the basic functions of a modeler - simulator for physical modeling which enables operator gestural control, and where the simulation processes are real time oriented. These constraints cannot be achieved by any kind of models and algorithms. Concerning the theoretical elements, the choice of the underlying Physics and the categorization of interactions will be presented.
We will then introduce the Cordis-Anima system, its constructive langage, its real time simulator and its force feedback gestural transducers. Finally, we will describe, with some examples, how we model, simulate and manipulate a large variety of physical objects and scenes with our system.

I. ANIMATION : SPECIFICATION OF A CREATION TOOL

Computer Animation has given rise to a large number of tools and methods based on frame by frame techniques that seek to preserve a cinema animation operating method. However, they do not enable certain motion qualities to be obtained, e.g. those that are phrased, natural, expressive, despite a refinement in interpolation methods [Ree81, SB85].

Consequently, Computer Animation turned to the physical laws that govern natural movements. Since the 80s, the OSU animation tools [Sch84] have integrated physical laws as a method for producing movement drafts. Later, the complete restitution of displacement and deformation by simulation of the physics of objects appeared in 1987 [TPBF87, Gas90, Dum90...]. It dealt with problems that were difficult to tackle with the frame by frame method - for example, rebounds on obstacles and continuity in movements. Simultaneously, some research has tried to introduce live aspects, such as obstacle avoidance, multitude behavior and processes of morphogenesis [Ree83, Rey82-87].

For its part, since 1978, the ACROE [Flo78, Cad79, Luc85-91, Jim 89] has introduced the notion of computer animation and computer music by physical models and gestural control. From the outset, we proved the interest for physical modeling in animation. In addition, we have also shown that physical modeling, and probably only physical modeling, enables efficient on-line gestural control integrating gestural perceptions.

Our present objective aims at designing and building a structured and well-defined tool - a "modeler - simulator for animation" based on physical modeling - rather than merely specific algorithms or simulations of physical knowledge. This implies designing and implementing a physical object modeler, a physical model simulator, and gestural control with force feedback. All these functions have been implemented into a compact and coherent system called CORDIS-ANIMA.

I.1. REVIEW OF PHYSICAL MODELS

Before tackling the design of the Physical Object Modeler-Simulator, we should draw up some of the major properties of physical models.
Modeling a natural object by geometrical models consists in extracting some topo-morphological invariants. The physical model seeks to represent other (physical) properties, in correlation with the topo-morphological ones. These properties are conveyed by physical invariants such as inertia, stiffness, viscosity distributions... "Intensive" variables (forces) are correlated to "extensive" variables (positions) to describe the object. However, to represent the peculiarity of a physical object, another specification of the topo-morphological levels is then therefore needed, to establish the correlation between the two kind of physical variables.

I.2. PREVIOUS RESEARCH [Gas 90]

Animation of rigid articulated objects deal with constant shape monolithic objects linked by various articulations. Research focusses on solving the complex systems of equations [AG85][Ver90]. The essential problems arise with operator movement control [IC87] and interactions between objects [Hah88][MW88]. The interaction forces depend on the geometry of the objects. The calculations are quite difficult and cannot be treated "in line".

Animation of deformable objects was firstly drawn from Continuous Mechanics that describes deformations under constraints for some categories of objects (homogeneous, isotropic, quasi linear). Because of their continuity with geometrical models, these models are widely used [TPBF 87][Dum 90]. Unfortunately, such models only cover a small behaviour scope between the rigid and the deformable; Complex materials cannot be simulated; and serious problems arise in interactions. A second approach based on discrete models allows modelisation of complex materials and enhances interactive control. Amongst others, there are meltable materials [TPBF 89], snake locomotion [Mil 88], deformable vertebrate objects [Gas 90], and the work carried out by the Acroe team.

II. PHYSICAL OBJECTS MODELER-SIMULATOR

Although the research we have referred to above has created splendid animation sequences, it is not geared towards a modeler-simulator to provide computer representation of a large variety of physical systems with which the animator can interact to experiment, search and control movements that have not been previously defined.

The modeler : It can allow the animator to build his own models. One major property of the modeler should be "modularity and variety". Not all modeling methods are suitable for this.

The simulator : To produce a large quantity of movements, the simulation must be on-line real time oriented. If movements can be controlled dynamically by human instrumental gestures, it can run in genuine real-time. Not all models and algorithms are able to meet this constraint.

Modeler-simulator relationship : Some CAD-CAM applications enable a lengthy compilation layer between the modeler and the simulator. Given the difficulty designing a physical model, simulation can assist the model design. The relation must be as flexible as possible.

II.1. METHODOLOGY

This section examines the four essential stages in designing a Modeler-Simulator in the specific field of physical objets :
Stage 1 - choosing a modeling principle
Different geometrical modeling principles (B-rep, CSG...) exist and present different properties. Similarly, the physical modeling principles affect modularity and real-time capabilities and must be explicitly chosen.
Stage 2 - the choice of the basic elements
They define the domain of expressiveness i.e. the set of achievable objects.
Stage 3 - the choice of the simulation algorithms
This affects modeler-simulator flexibility and the real time features.
Stage 4 - outside communications and global integration.
This defines the relation between the animator and the computer tool.

II.2. CHOICE OF A MODELING PRINCIPLE

II.2.1. The analysis of different model-types

Prerequisites review:
* The model quality is induced by human actions and perceptions ;
* The variety is thus defined by the animator's needs, which may be several kinds of natural or constructed objects (hightly deformable, very rigid...) which could quickly interact, merge... etc.

We have thus conducted a consistent analysis of the model-types proposed by Physics and the Engeering Sciences, to extract a principle adapted to this modeler-simulator approach.

We distinguish three model-types :

1 - the continuous distributed model
The object is described by a system of partial second order time differential equations. The solutions can only be found in specific cases such as time-independent coefficients, constant coefficients, coefficients with partial derivatives in specific cases (homogeneity, isotropy...), small strains or displacements. This model is marginally appropriate in describing large non-linearities (inhomogeneity, anisotropy...). Despite these obvious shortcomings, it was often widely chosen [TPBF87, TF 88].

2 - The continuous lumped constant model
When the objects are too complex or too little known, prior structural discretisation is carried out, thus breaking down them into components, each being described by the above differential equations system. In fact, the constants localisation principle introduces the notion of "component", and it can see as a language, i.e. as a representation that gives rise to object creation by assembling components.

3 - Models taking non-linearities into account
Natural phenomena are extremely non-linear, such as border phenomena (collisions...), or material transformations (agglutination, plasticity). These cannot be represented in a equational form and require state sequencing representation. The latter can be achieved by the previous "components formalism" in which some components are linear and others non-linear .

For these reasons, only lumped constant models can be taken as a basis for a physical object modeler.

II.3. CHOICE OF COMPONENTS FOR THE MODELER

II.3.1. Component categories

Physics describes the evolution of continuous bodies by two classes of laws:
* Fundamental laws, also known as "conservation laws" or "matter laws" ;
* Behavioral laws also known as "constitutive laws" or "material laws".

The fundamental laws are general. Basically, Newtonian laws define the notion of force, its associated notion of mass, and the action/reaction principle.

These laws do not enable complete description of object evolution which equally depends on the constitutive materials. These can be accounted for by basic rheological behaviour "elasticity" and "viscosity". "Plasticity" and "Fractures" are often added, although they are empirically known. The physics of materials is thus akin to a library of behaviour.

There are still less general laws of macroscopic interaction. In Mechanics, only very specific interactions cases, which are extremely dependent on object geometry, are studied. General interactions are only listed in the physics of the material point (gravitation, cohesion forces, collisions...).

A "good categorization" for a modeler-simulator approach should enable complex phenomena (plasticity, agglomeration...) to be decomposed and recomposed into more elementary phenomena. One preliminary question then arises : What categorizing similarity or dissimilarity can we bring about in the bodies, or system of bodies ? For example, there is a great difference between a visco-elastic material and a plastic material. The former can be represented in a equational form; the latter require state sequencing representation. On the other hand, collision and plasticity are fairly similar. Both include state sequencing representations, the first to describe non linear phenomena located onto macroscopic boundaries, the second, to describe microchanges in material.

This has led us to split material behaviour into linear and non-linear rules. This decomposition is not a classical breakdown because it forces us to treat some very different physical phenomena in the same manner.

II.3.2. Components in CORDIS-ANIMA

II.3.2.1. Matter element
Newtonian laws entail explicit relations between the forces and positions that are necessary to connect the simulated object to the external universe by means of sensors-actuators that convey explicit physical variables.

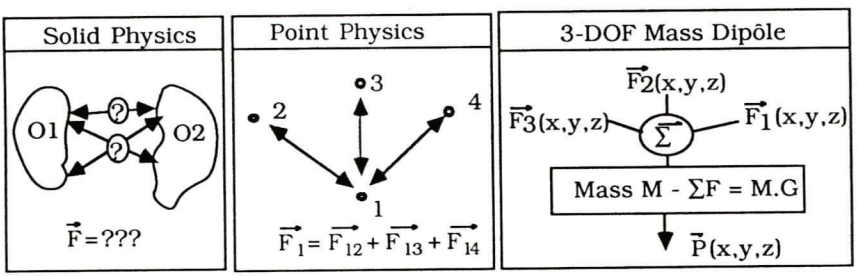

Figure 1 - Matter Element

In a modular approach, we can put physical objects in interaction. Solid Physics, conveyed by the "infinitesimal solid" kernel, essentially studies the behaviour of bodies themselves; it cannot tackle the border problems with large non linearities. We must choose Point Physics even when we need a great number of punctual masses. In this case, a piece of matter comes to be described by an aggregation of several punctual masses. This formalism gives access to micro or macrostructures, homogeneous or not, and it is well adapted to a real time approach. In contrast to Solid Physics, the interactions calculus is always possible. Localisations, directions and values of the forces are always known: localisations are onto punctual

masses and the directions and values are given by the vectorial sum of forces. In the CORDIS-ANIMA formalism, the matter component is a 3-DOF dipole(fig 1).

II.3.2.2 Linear material elements
Linear behaviour is very simple to represent and simulate [Cad 79] [Luc 81-90] [TPBF 87][Gas 90]. Note that only linear elasticity and linear viscosity are required, because they provide the two sufficient linear rules between forces and positions for the first, and forces and speeds for the second. They can be represented by a 3-DOF quadripole component {(F1,F2), (P1, P2)} (fig. 2).

II.3.2.3. Non-linear elements
Non linearities are more difficult to design and implement. To obtain a "good categorization" for a modeler-simulator, we distinguish between two kinds of non linearities :
* continuous non linearities, for example, the dependence of the stiffness on the position (fig. 2)
* discontinuous non linearities as collision, plasticity, fractures, but also more complex interaction as adherence or rack and pinion steerings...

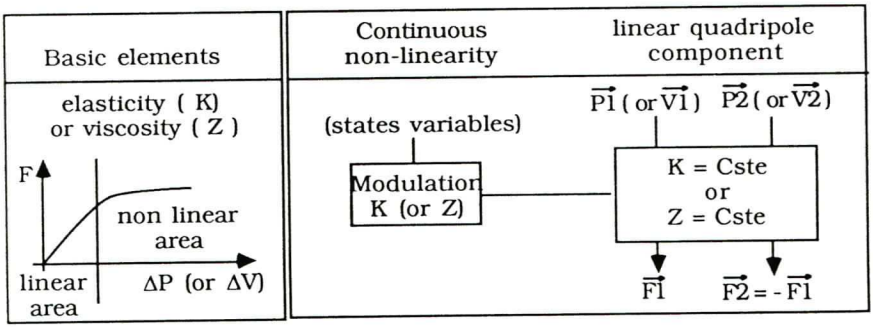

Figure 2 - Basic rheological elements

If we call "parameters", the constants of inertia, stiffness or friction, the first case of non linearities can be dealt with in the Cordis-Anima system by "parameter modulation" (fig. 2). The physical parameters can be dynamically modified by any state variables such as positions, speeds or forces during the simulation, in real time. This provides complex behaviour, such as non linear oscillations, relaxation phenomena...

Collisions are the simplest case of discontinuous non linearities. In this case, as in similar instances (fig. 3 : plasticity, cohesion interaction), the output interaction variable, for example the force, depends on a single variable, for example position. We can then represent interactions by piecewise linear functions and defining a generic algorithm for them is relatively simple.

But in the more general case, like dry-friction, (fig. 3), rack-pignon steering ..., the output interaction variables depends on several state variables, for example, simultaneously positions and speeds, and this, according to a complex sequence of conditions.
In general, interactions are composed by numerous but finite states. We have implemented, in the Cordis-Anima system, a general formalism for them, based on a finite state automata formalism, named "conditional links" (fig 4). The state of linear interactions (stiffness and viscosity) are managed dynamically by finite state automata according to the values of state variables. It is therefore clear that piecewise linear functions are a special case in this formalism.
Because of the punctual decomposition, in which the forces are summed onto the masses, composite and complex interactions can be built by putting all the interactions (linear or not) in parallel.

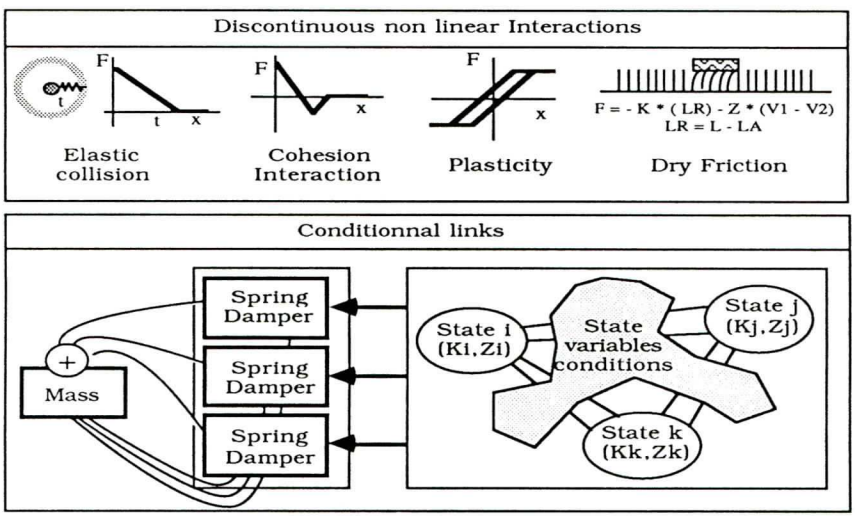

Fig. 3 - Discontinuous non linear interactions and Conditional Links

II.4. THE CORDIS-ANIMA MACHINE

We can now give the general structural model of a physical system in the Cordis-Anima Machine.

A linear physical object is represented in the CORDIS-ANIMA formalism as a set of interconnected punctual masses linked with linear stiffness and viscosity. Non linearities are conveyed by parameter modifications and by state changing of the physical interactions. Note that in this approach, the decomposition of the objet, that is, the network structure, is not only geometrically, but more topologically, dependent. It is more the structure

of the network than the geometrical data, that represent the scene. For example, we can specify in the network all the interconnexions that represent all the possible interactions.

Thus, in Cordis-Anima system, objects in their linear behaviour, have been represented by a planar network of only two components :
* mass components, which calculate positions from forces
* interaction components which calculate forces from positions
The association rules are the Kirshoff rules : Mass components can receive several interaction components and interaction components can link only two mass components. In formal terms, a Cordis-Anima object can be described by a looped graph, which has two kind of nodes, and in which the connexions between the nodes are constrained by assembly rules.

Each algorithmic element (matter or interaction) can thus be calculated by different methods, the simplest and quickest being the finite differences methods. The various finite difference calculation methods introduce specific approximations which affect modularity. They are not dealt with in this paper, but they have been discussed elsewhere [Ora90].

All components, be they interaction or mass, can be run in parallel. Object s are composed of a large number of these small algorithmic simple dynamic behaviour components. In terms of a network of simple interconnected components, this approach is highly suitable to current computer technology developments. These components can be clustered into two blocks (Fig 4): a masses block and an interactions block.

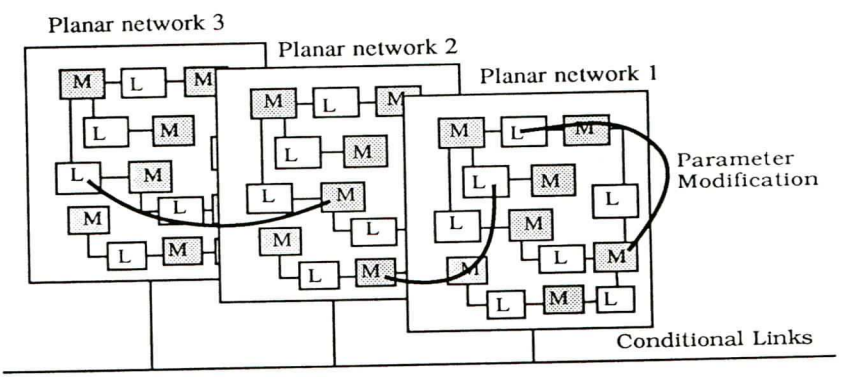

Figure 4 - The simulator architecture

In their linear components, objects can be mapped onto a large homogeneous network with only two kind of algorithms which run in parallel. But, because of conditional links, this plane becomes duplicated according to the number of states of the conditional links. And, because of parameter modification, there are internal connexions, which are orthogonal with the links defining the planar linear networks (Fig 4).

III. FROM MODELER-SIMULATOR TO THE CORDIS-ANIMA SYSTEM

The modeler-simulator described in the previous sections is one part of the entire CORDIS-ANIMA system, which also features a set of force feedback gestural transducers, a real time visualisation processor and a real time sound processor.

III.1. FORCE FEEDBACK GESTURAL TRANSDUCERS

We distinguish two kinds of gestures :"symbolic gestures" such as "pick and place", and "instrumental gestures". The "instrumental" gesture develops when an object is physically manipulated. This gesture is bidirectional : we act on the object and simultaneously, we feel the object, by sight and hearing, but also by our tactilo-proprio-kinesthetic perceptions. If the physical object is in a computer virtual form, we need a special force feedback device to act on it and perceive it via the gestural channel. Atkinson [Atk 77] has the idea of a 6 DOF force-feedback device and now some compact force feedback devices have been built [Min 90][Iwa 90] [Ouh 88]. Since 1978, we have built several of these devices[Flo78,Cad81], called "TGR" (="Retroactive Gestural Transducers").

Our latest "TGR" has sixteen degrees of freedom and the set of "actuator-sensors" have been designed according to :
* compactness : it is a slice sensor-motor mounted in a linear form in which each slice is 13,75mm thin.
* adequacy : to have simultaneously, energy, velocity, and precision required by the human instrumental gestures. We can restitute a shock on a rigid surface in which the device develops about forty or fifty newtons, and where the bandwidth of the electromechanical parts are about 1 KHz for each degree of freedom. In addition, we have restituted the friction on a granular surface. The device allows us to feel a few microns of resolution.

Furthermore, this device provides double modularity : (1) electromechanical modularity: the motor principle allows slices to be added ; (2) mechanical modularity - the transducer has been designed to receive mechanical interfaces adapted to different categories of gestures. Currently , two mechanical interfaces have been mounted on : a 2DOF stick and the "2D-thimbles" (Dés-2D in French), which are two 2DOF sticks [Photo Acroe1].* By sliding your fingers into the rings, objects can be grasped, dragged, or compressed. Their reaction can be felt, for instance, their gestural resistance to deformation or displacement.

III.2. TIME FACTORS

Three real time sensory-motor loops are required to manipulate an object: (a) gestural action to tactilo-proprio-kinesthetic perception; (b) gestural action to visual perception; (c) gestural action to acoustic perception.
The overall object simulation speed must therefore reduce the delay between the action and the three resulting perceptions to an

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* See page 545 for Photo Acroe 1

imperceptible level. The actions are sampled between 25 Hz to 1 Khz. At each step (basically 1 ms), 16 gestural I/O, physical object/physical interactions simulations, and visual and acoustic outputs are performed. All examples shown in this article are generated according to these time specifications, onto a special architecture composed of 6 processors linked by synchronous parallel channels.

III.3. EXAMPLES AND SIMULATIONS

This section briefly describes some of the simulations our system has carried out. Unfortunately, it is difficult to illustrate real time animations with a few photographs. However, a video tape containing all these examples is available at the ACROE laboratory.

Example 1. Feeling with gesture
A surface is simulated, which produces dry friction if we move over it. We use two degrees of freedom with the TGR. We come down on the surface, detect it, and feel its resistance and its hard non-penetrability. Then, we move across the surface and we feel the drag of its adherence. The surface is more or less sticky. Simultaneously, we can hear a characteristic finger-glass interaction screech .
Example 2. - Physical falls
Numerous physical particles are in physical interaction between themselves and between rigid obstacles. Optimal stacks can occur.
Example 3. Highy deformable object
It oozes down the stairs, moulds itself to the steps, rotates, slides, and stops against a wall [Photo Acroe2].*
Example 4. Non stable shapes
Particles are linked by cohesion forces, and they are stable if the internal forces are greater than external forces. You can obtain non stable arrangements. The object, in our conception, is a relative notion.
Example 5 - Deformable and rigid objects with real time manipulation
A more or less soft deformable bar falls onto rigid obstacles. Notice that all the objects, here the rigid obstacles, can be manipulated by the operator in real time, by means of the TGR. The movements are very tonic thanks to a high simulation sampling rate.
Example 6 - A rattle
The toy is manipulated in real time, and the operator feels the shocks of the cube on the manipulated sphere
Example 7 - Fluids.
There are deformations, fractures and re-sticking. This is yet another demonstration of the relativity of the notion of objects [Photo Acroe1].
Example 8 - A gelly like simulation
This object is a block of matter, a GELLY like example. The operator kneads the paste with the "2D-thimbles". He feels the resistance of the paste. Notice the fractures and the re-sticking. [Photo Acroe1].
Example 9 - Plasticity
A mere parameter modification from our previous example obtains plasticity. The object retains its former shape. The operator can tears the paste into several pieces and re-stick it. He can feel its plasticity [Photo Acroe2].

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* See page 546 for Photo Acroe 2

Example 10 - sound falls
Movements and sounds produced by the same model. The scene is similar to the falls in the first example, but the rigid obstacles are drums.
Example 11 - Vehicles moving over ground with obstacles
There are several kind of rigid articulated vehicles with high degrees of freedom. They drive over some ground obstacles and avoids others. The interactions are non penetrability, dry friction driving the wheels, and physical avoiding. The ground can be more or less rigid [Photo Acroe3].

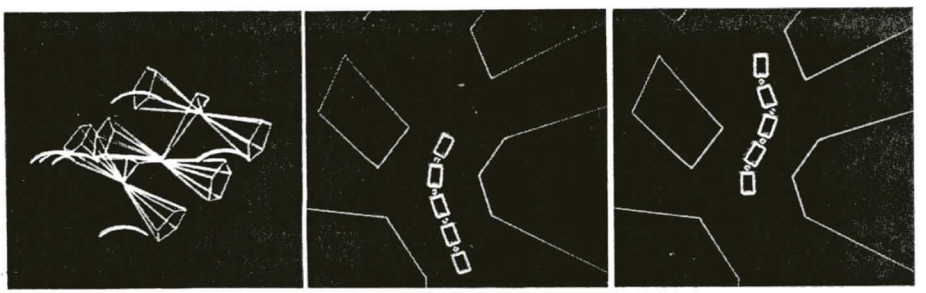

Photo Acroe3 - Rigid articulated vehicles driving over and avoiding obstacles

Conclusions
The CORDIS-ANIMA system, with its modeler, its simulator, its Retroactive Gestural transducers, and its real-time acoustic and visual outputs constitutes a complete tool for building, experimenting and perceiving "Virtual Realities". Indeed, it is a good example of what we call an "Instrumental Communication Interface", in short a tool to communicate physically with any kind of Computer Object.

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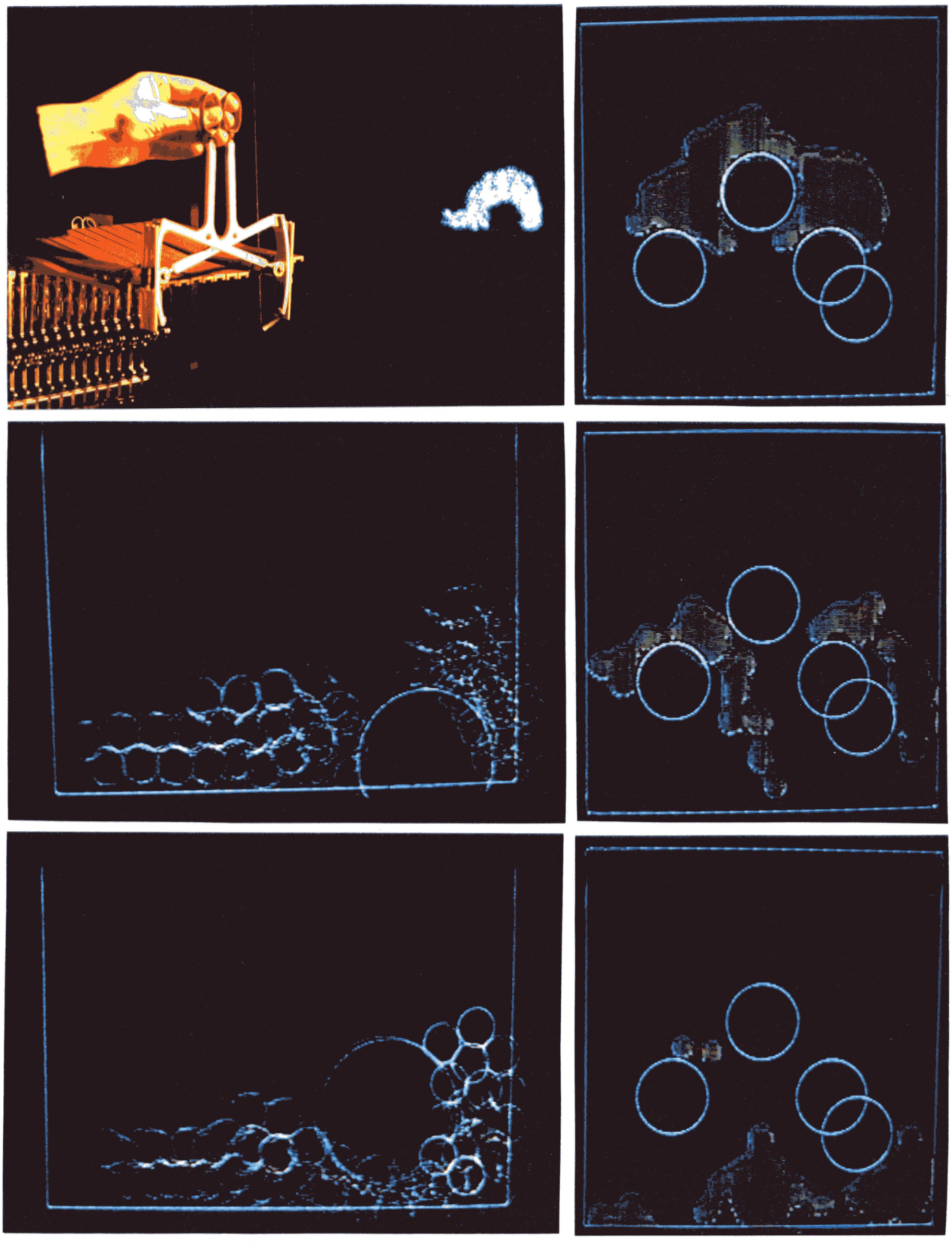
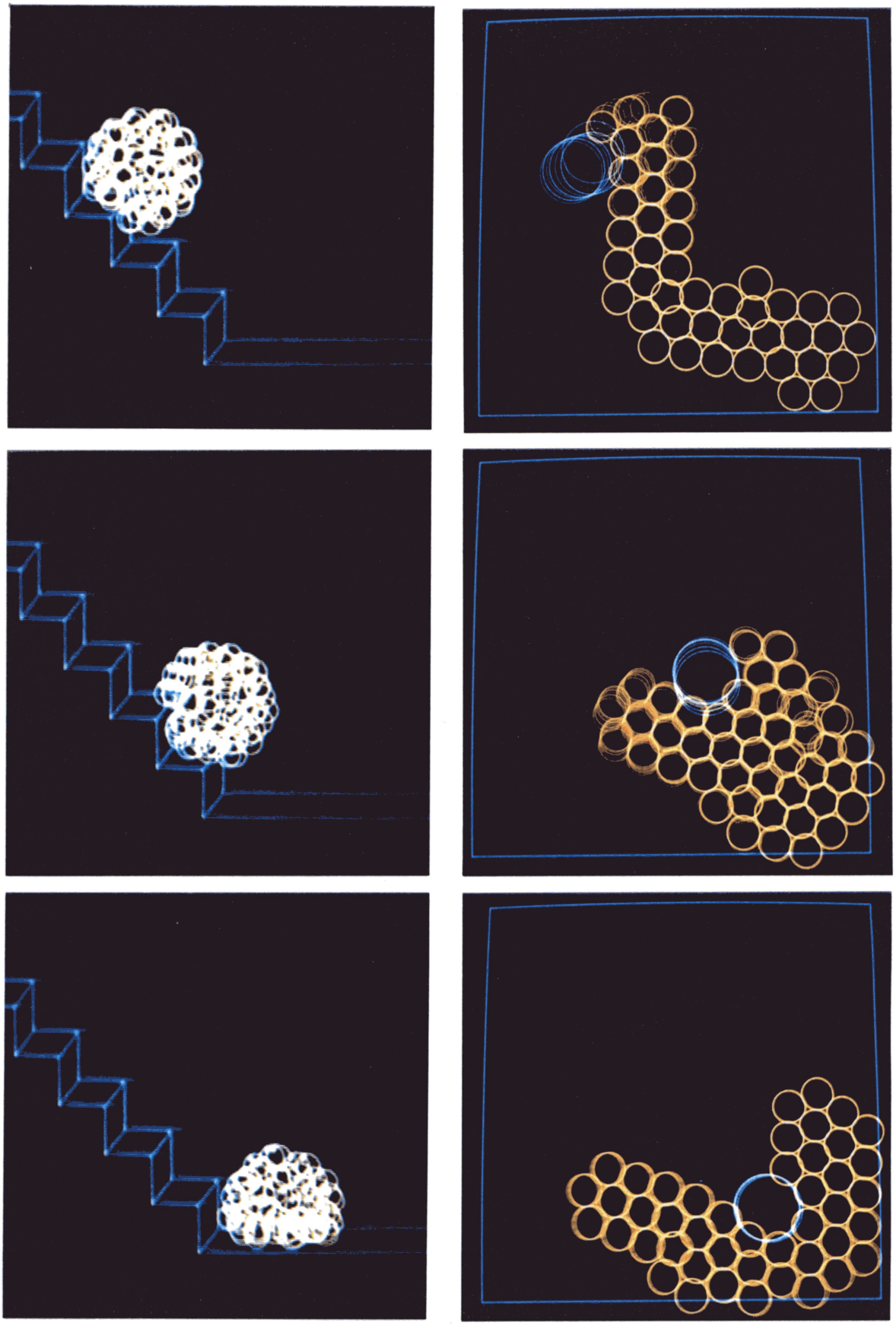


- Photo ACROE1 -

(a) the Retroactive Gestural Transducer "2D-Thimbles" - (b) Real time manipulation of a piece of deformable paste - (c) Fluids



- Photo Acroe2 -

(a) Highly deformable object - (b) Plasticity with force feedback action