ANIMATING HUMAN FIGURES: PERSPECTIVES AND DIRECTIONS

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ABSTRACT

The overall goal of our work is human motion understanding. In particular, motion performance, observation, description, and notation impacts the form of a motion representation. A representation can be verified by a computer graphics performance, and thus the effective control of natural-appearing human figure movement is a significant and challenging goal. Characteristics of a computationally realizable human movement representation are discussed, including distinctions between hierarchic levels, kinematics, and dynamics. The qualitative factors of Effort-Shape notation are used to suggest extensions to existing movement representations in directions consistent with known characteristics of human movement and conventional animation. We show how useful and expressive motion qualities may be at least approximated by a combination of kinematics and dynamics computations, with kinetic control modulated by acceleration and decelerations derived from existing interpolation methods. Interactions between motions by phrasing, temporal properties, or relationships may be described and executed within an appropriately detailed model.

RÉSUMÉ

L'objet de notre étude est la compréhension du mouvement humain. Plus particulièrement, le fonctionnement du mouvement, son observation, sa description et sa notation ont un impact sur l'organisation de la représentation du mouvement. Celle-ci peut être controllée à l'aide de l'informatique graphique, mais un control adéquat du naturel de l'apparance du mouvement du corps humain est un défi à relever. Différentes caractéristiques de la réalisation du mouvement par informatique sont examinées. On distingue notamment la kinématique, la dynamique et les niveaux hyérarchiques. Les facteurs qualitatifs d'une notation "Effort-Shape" précise sont utilisés pour évoquer l'extension de la représentation actuelle du mouvement vers une une direction compatible avec les caractéristiques courantes du mouvement et de l'animation. Nous démontrons comment certaines qualités significatives du mouvement peuvent être approximées par la dynamique et la kinématique avec le control de la cinétique modulée par l'accélération et la décélération ces deux dernières étant dérivées par les méthodes d'interpolation conventionnelles. L'interaction entre l'expression du mouvement et les propritées temporelles peuvent être décrites et exécutées selon les limites d'un modèle pertinnement détaillé.

KEYWORDS: Human movement, motion understanding, movement representation, computer animation, simulation, computer graphics, dynamics.

EXTENDED ABSTRACT

INTRODUCTION

A significant portion of our activities and perceptions are associated with the performance, observation, description, or recording of human movement. It is a challenge to the current state of knowledge in Computer Science to similarly represent, simulate, and integrate these differing manifestations of human movement since they touch on such seemingly diverse areas as computer graphics, computer vision, robotics, and computational linguistics [6]. In this exposition we shall discuss the philosophy and methodology behind our research into the computational understanding of human movement, concentrating on the issues of movement representation, movement synthesis, and task specification. While our primary emphasis will be on performance, that is, the animation or simulation of natural human motion, we cannot avoid inquiring what our representational decisions would imply for a general theory of human movement understanding.

We will try to examine human movement in the most global view possible, namely, that a movement representation should be at least sympathetic to the needs and character of each modality: performance (or control), observation, language description, or symbolic recording. Our own research, and certainly that of others, has touched all these areas: for example, computer graphics for human motion synthesis [9, 16, 65, 33, 41, 38, 21], computer vision for motion and shape analysis [46, 1, 36], movement notations for symbolic motion representation [29, 63, 9, 15], language analysis for motion verb characterization [45, 4, 23], and robotics for path planning and goal-directed behavior [35, 34]. Having originally examined motion descriptions based on visually-observable data [4], the inadequacy of this view by itself is keenly felt. Such descriptions may serve as a target for information reduction, but are apt to be the product of convenience dictated by the observational task at hand. Such a description differentiates between phenomena of interest, possibly incorporating rudimentary notions of direction, velocity, and shape. Likewise, representations derived solely from language [56] omit essential information needed to reconstruct an acceptable performance.

By turning to representations derived from graphical performance or physical object control (for example, robotics), we get a different perspective. In particular, representations based on these end products will have the property that a graphical or physical *performance will verify that a representation is adequate to characterize some* (hopefully broad) *class of human movement.* It is this *adequacy* that permits experimentation based on empirical data (say from observed movements) and parametric variation to control or tune the result.

The role of natural language descriptions is to expose the salient features of human motion interpreted (by a culture) as significant events. In particular, we find language has evolved rich verb and adverbial vocabularies to permit the description and expression of subtle movements. In fact, language goes even further by imputing behavior, emotion, and intent to movement, even when that motion is not obviously attributable to human-appearing agents [44]. While such information is available subconsciously via our cognitive systems, it may also be instantiated in language (or physically acted out, for that matter). Therefore we assume the existance of a transformation which maps some of these subconscious perceptions into tangible (and essential) components of a motion representation. It appears that some of this information can be captured; how much is not clear, though we will propose a model here.

Finally, we use movement notations as a source of symbolic representations derived from empirical observation and analysis over many years by many observers of numerous subjects. The impact of such systems is that they provide one of the only possible bases for establishing *completeness*: that is, does the representation cover, in its variations, the known scope and range of human movement? Language also provides some of this scope, but does not lend itself so readily to analysis.

We proceed by examining some of the representational issues which arise in considering the influence of these requirements.

REPRESENTATION REQUIREMENTS

Movements of human or robot agents may be characterized at many different levels. A purely geometric level of description as changing coordinates, though necessary, is insufficient as a comprehensive basis for understanding motion. A simple gesture such as closing the hand may be described by joint angles, by paths of the fingertips, by flexion of muscles, by the concept "grasp," or by the intention "shake hands." Each type of description is useful in different contexts, and a natural hierarchy of levels seems to appear. To discuss a movement representation therefore is to establish what descriptive levels are important and what attributes or characteristics are adequate to completely "cover" the space of possible movements at each level. We will return to this issue later, after establishing a plausible representation scheme in which to formulate higher level motion or action descriptions [22].

Viewing movement hierarchically focuses attention on descriptive or conceptual levels, that is, the refinement or generalization of a movement at a different level of detail. Performance of a particular motion, however, requires the interaction or combination of effects from many sources. While geometric object descriptions lend themselves to a hierarchic view [18, 8, 42], motions are dictated by simultaneous interacting influences. Muscle tension, external forces, joint limits, path constraints, expressive purpose, intention, and the context of temporally adjacent activities all affect human movement. A more general approach to movement understanding therefore would cover at least the following aspects of a motion.

- The geometry, kinematics, and dynamics of the agent.

  The individual differences in people and their anthropometry must be taken into account. Motion is significantly affected by the kinematics of jointed objects, such as joint limits, reachable points, and comfort zones. Dynamics describes the force or effort influencing motion, whether actual or perceived, and may be independent of motion path. Dynamics also involves the inherent strength of the agent to initiate or resist motion.

- Any goal-directed or intentional acts the movement was part of.

  Much human motion is intentional, even if unconscious: the achievement of reach goals, negotiation through a space, maintenance of balance, and comfortable distribution of weight.

- The agent's attitude toward the environment, and its general mode of behavior.

  The interpretation of any particular motion is highly dependent on the environmental and personal context: thus a "threatening" gesture in a social context may be merely "defensive" in an athletic one. Motions which are part of an ongoing task or activity may be perceived as more global entities rather than isolated movements.

- What, if anything, it signified.

  For example, sign language research [31] shows that certain seeming variations in a movement are understood as the same sign, while others are not. Often movements along the same spatial path and toward the same spatial goal may signify very different intents, such as "touch, "press" and "punch."

- Any synchronization or concurrency relations the movement depends on or is derived from.

  Motions may occur in isolation, in sequence, in parallel, or in any overlapped or superimposed combination. Some of these relationships were studied in the motion context [10], in language [2, 62], and in task-level reasoning [61, 22]. They may also overlap, mask, dominate, accentuate, or modify one another, as has been demonstrated with facial motions [52, 53]. The movements may occur compressed or extended in time, or be subject to environmental constraints or control requirements. For example, the actions of a group of athletes on a team is subject to the rules of the game as much as the particular instantaneous circumstances of the play.

Of course, these factors are not orthogonal to one another, but interact and interrelate in complex ways. Part of our task is therefore to organize motion information so that we can hope to control motion to the extent that the different factors can be investigated at appropriate levels.

The central "core" of the movement understanding methodology is a movement representation and its interpretation by computer simulation. The reason we insist upon interpretation will be clarified further in the next section. In succeeding sections we will examine particular aspects of the motion representation and show how each component is essential to effective motion synthesis and how its semantics might be implemented.

MOVEMENT REPRESENTATION

In keeping with the general concerns expressed above, we enunciate several criteria deemed essential to the design of an effective motion representation. To focus the effort, we will define a movement representation as a system in which *any movement may be decomposed into "primitives" with implementable semantics.* We require these primitives to meet certain constraints:

- descriptive significance

This issue implies that mere visual images are not sufficient for a motion representation; even an extensive "film library" is not in the form of primitives that may be readily used as the basis for simulating arbitrary motion patterns. There is no index upon which similarity or differences between two motions may be easily judged. There may not even be agreement between observers as to the name or type of motion being performed. The fact that most imagery is two-dimensional is an additional complication, but if the images were from multiple viewpoints or even holographic, the objection would still stand.

A similar objection can be raised to descriptions consisting of natural language text. Though there may be cultural agreement on the meaning of an utterance, the actual process of converting the description to action may be subject to widely varying interpretations, for example, via "acting."

- modifiability through generally accessible methods

This issue implies that a motion representation must permit the symbolic or computational modification of a motion primitive in order to create a wide class of related or similar motions. "Generally accessible" implies eliminating choices such as libraries of artist-drawn animations, since the creation of natural-appearing hand-drawn animations is not a widespread skill. At the minimum, this constraint argues for parametric descriptions, though we need not commit to a specific set of parameters yet.

- independence of specific individuals

This issue again rejects the film or artist-drawn library approach, and also disallows more detailed but still joint- or segment-specific motion data collected from an individual. Thus while such motion may be used as the basis of a specific animation [15, 24, 21], it is not obvious how such a motion would change if it were applied to another individual with different body dimensions, weight, strength, posture, *etc.*

- independence of specific motion characteristics

This issue emphasizes the need for a parametric approach, though now the problem is the motions within an individual and the possible ways they can be combined, compounded, executed in parallel or sequence, inhibit or permit other motions, *etc.* Thus the primitives must describe possible actions of body components and be subject to synchronization and modification by other primitives. In addition, we expect physical factors to be separable: for example, the path of a motion should be separable from the kinetics of motion along the path. Again, representations of the library type cannot deal effectively with the computational explosion of possibilities inherent in arbitrary human motion.

In constructing a movement representation we have been very concerned with its capabilities to describe sufficient information for a "performance" by computer synthesized graphic images [9]. This point of view has been very fruitful in deciding what characteristics of a movement description and hence of an adequate representation, are necessary. The important concept is that movement synthesis considerations demand consistent implementable semantics. If a computer system could produce any movement specified by the appropriate descriptive parameters, then it would also verify that a representation was an adequate knowledge base with which to describe or notate observed movement. Thus, for example, if the representation cannot express the differences between "press" and "punch," it would not have sufficient means to distinguish these actions if actually observed.

Symbolic representations of many movement properties are found in Labanotation [29], a movement notation system originated over 50 years ago by Rudolf Laban. Though several notation systems exist, few come close to meeting the criteria for a movement representation. We initially studied Labanotation [9], basing the choice on several factors deemed essential for effective motion specification:

- its redundant means of expressing a movement
- its methods for handling sequence, concurrency, and phrasing
- its capabilities for arbitrary frames of reference
- its incorporation of goal-directed actions
- its essentially "digital" symbol system.

We abstracted these Labanotation properties into a set of five "primitive movement concepts" [63] (*directions, revolutions, facings, shapes,* and *contacts*) concerned only with the location and relations of body joints or surfaces in space. Significantly, these primitives do not cover dynamic effects (force, acceleration, torque, etc.), muscular movements (bulges, contractions, etc.) or facial expressions [52, 48]. Thus a motion specification in this system actually describes the final goal and some constraints on the path rather than the internal method by which it is achieved [5]. *Directions* generally describe positions to be achieved by body parts, or directions in which the entire body is to move. *Revolutions* include rotations and twists by given angles. *Facings* are goal-directed rotations which require a body surface to achieve a desired orientation. A *shape* is either a path along which a body or body part moves, or a spatial shape (position or configuration) which some subset of the body is to achieve. *Contacts* are generally relationships such as touches, supports, contains, *etc.*, between two or more bodies, body parts, or environemental points. All the primitives share notions of duration, fixed end, and reference coordinate system.

We have recently come to view movement somewhat differently. The evolution of this early motion representation is motivated not only by current efforts in three-dimensional computer animation [38, 41], but also by practice in robotics [50, 40, 27, 49, 20] and motion analysis [46, 60]. We distinguish four different kinds of movement primitives:

- "Changes": rotations by a given angle or translation along a given path or direction
- "Goals": achievement of a given location and/or orientation for a body point [35]
- "Paths": curves in space along which points may move
- "Dynamics": kinetics or forces which control or affect a motion

The former "primitive movement concepts" are easily subsumed into the first three of these four primitives. The new primitive, *dynamics*, will be discussed in the next section. A comparison of the categories of the "old" representation [9, 63] with respect to this new representation appears in Table 1.

In Table 1, a *reach* refers to the kinematic achievement of a location in space by some body point and an *orientation* to the kinematic achievement of an orientation of a body point. The "key-parameter" concept refers to a set of parametric values for particular manipulable variables of the body such as joint angles, reach position, body location, *etc.*

Changes, goals, and paths must have associated with them durations, starting times, and reference coordinate systems. We can assume that the original specification is adequate in that regard [63]. Items such as fixed ends of a reach goal are indicated by zero changes in that body point in an appropriate coordinate reference

Table 1: Comparison of "old" and "new" movement representations.

"old"	"new"
DIRECTION (movement)	**Change in position**
DIRECTION (position)	**Reach goal**
REVOLUTION (rotate)	**Change in orientation**
REVOLUTION (twist)	**Change in orientation**
FACING	**Orientation goal**
SHAPE (movement)	**Sequence of reach goals or "key-parameter" locations**
SHAPE (position)	**"Key-parameter" positions**
CONTACT	**Sequence or set of reach and orientation goals**

frame [5, 25]. Thus the shoulder might be the fixed end for an arm reach to position and orient a hand with respect to some object. The former *contact* primitive is subsumed into time-marked sets of one or more goals achieved sequentially and in parallel as needed. The semantics of *determining* those goals is left to a higher level process [7, 65, 23, 22].

The task of synchronizing concurrent actions and handling multiple constraints is passed to a control system rather than being explicitly embedded in the representation. A parallel control algorithm had been advocated earlier for this purpose [9]. The essential features of this control were

- joint "processors" which interpreted parallel streams of motion primitive "instructions" as programs,
- a special processor to handle movements of the center of gravity, and
- a global monitor to synchronize local changes to a global, constrained, body model and thus process concurrent overlapping motion primitives.

We can relax the control model by viewing the body parametrically, that is, any specified point on the body may be controlled by specifying a sequence of one or more values over time for it. Paths are themselves a sequence of parameter values. The parameter values may be affected by more than one primitive, for example, the position of the body's center of gravity may be affected by the path of movement, inertia, and external forces [9, 25]. It is the responsibilty of the animator and the simulation semantics to resolve any discrepancies [10, 53]. The particular interactions of the *dynamics* primitives are new and will be examined carefully in the next section.

DYNAMICS

A key feature of human movement virtually ignored in earlier representation efforts is its dynamic quality, that is, the manner in which the body moves in terms of *force, effort, exertion, energy, etc.* This may be more significant, in an expressive or intentional sense, than the actual path. For example, variations in dynamics can alter the message conveyed in American Sign Language [31, 39]. Dynamics considerations appear only implicitly in the representations derived from the study of movement notation systems because:

- Labanotation (or for that matter, nearly any other notation) does not convey dynamic information other than timing (duration) and perhaps *accent*,
- Motion semantics have been mostly concerned with *visually smooth* implementation of each primitive motion, not of the *details* of that motion during its execution nor with its continuity in the context of temporally adjacent motions, and
- The computational models must include capabilities for understanding some minimal physics associated with body mass, force, inertia, gravity, balance, *etc.* [10].

Computer animation done without concern for motion dynamics looks flat or mechanical at best; discontinuous or jerky at worst.

Previous efforts at incorporating dynamics into computer generated animation have focused on explicit velocity or acceleration functions [43, 58, 17, 26], artist-drawn keyframes [14, 54], smooth spline functions [57, 59, 32], or actual human dynamics [15, 11, 66, 24]. The problem has been investigated more mathematically in mechanics [47, 30, 51], biomechanics [55], and robotics [27, 37, 13, 28], though the latter has been much more concerned with computational efficiency. Recently, such techniques have been applied to human or articulated figure dynamics [3, 64, 25]. Our own examination of the dynamics problem has focused on alternative notation systems combined with physical and graphical motion models suited to the complexity of the human figure.

In searching for a representational basis for the dynamic qualities of movement, we examined a notation system complementary to Labanotation called Effort-Shape notation [19, 12]. Unfortunately, the semantics of this system are not defined quantitatively, so we have interpreted it freely to produce something more amenable to computation. We believe this to be a reasonable approach since our intent is not to "computerize" Effort-Shape, or another notational system as we and others have attempted to do. Rather, we use these systems to aid in comprehending the scope and variety of human movement so that our representations are more likely to cover the space of possibilities. In the remainder of this discussion we describe the influence of dynamics considerations on a motion representation and sketch possible implementations of its semantics.

SUMMARY

The need for better animation control is apparent from the literature. The qualitative factors of Effort-Shape notation are being used to suggest extensions to existing movement representations in directions consistent with known characteristics of human movement and conventional animation. We show how the motion qualities may be at least approximated by a combination of kinematics and dynamics computations, with kinetic control modulated by acceleration and decelerations derived from existing interpolation methods. In addition, the interactions between two motions by phrasing are handled explicitly by modifications expressed in the representation. Temporal, spatial, and relationship interactions may be described and executed within an appropriately detailed model.

Several animation systems are running or are under development at the University of Pennsylvania to demonstrate the feasibility and efficacy of these approaches. We are anxious to experiment with them and produce animations showing processes involving the interaction of several people with a complexity not yet demonstrated elsewhere.

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