A Knowledge-based Approach for Lifelike Gesture Animation

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Abstract. The inclusion of additional modalities into the communicative behavior of virtual agents besides speech has moved into focus of human-computer interface researchers, as humans are more likely to consider computer-generated figures lifelike when appropriate nonverbal behaviors are displayed in addition to speech. In this paper, we propose a knowledge-based approach for the automatic generation of gesture animations for an articulated figure. It combines a formalism for the representation of spatiotemporal gesture features, methods for planning individual gestural animations w.r.t. to form and timing, and formation of arm trajectories. Finally, enhanced methods for rendering animations from motor programs are incorporated in the execution of planned gestures. The approach is targetted to achieve a great variety of gestures as well as a higher degree of lifelikeness in synthetic agents.

1 Introduction

The communicative behaviors of virtual anthropomorphic agents, widely used in human-computer interfaces, are increasingly extended by additional modalities besides speech in order to achieve a more natural, efficient and reliable communication link between human and machine. Besides the increased robustness of communication, humans are more likely to consider computer-generated figures lifelike when nonverbal behaviors are displayed in addition to speech. This in turn, enables the evocation of social communicative attributions to the artificial agent, e.g. internal states, communicative intent and social responses [2], which increase efficiency and smoothness in human-human communication. Coverbal hand-arm gestures, which are an integral part of human-human dialogues and therefore ingredients of practiced communicative skill, are first candidates for extending the communicative capabilities of such virtual agents. In our work, we focus on the production of coverbal gestures of an articulated agent, i.e. gestural movements accompanying speech flow, which must meet several requirements simultaneously:

- spatiotemporal features of the intended gesture must be produced properly, i.e. spatial features like handshape and trajectories as well as kinematic characteristics like sudden halts
- gesture and speech must be coordinated sensitively with respect to their semantics and pragmatics
- gestural movements must fulfill severe timing constraints resulting from temporal synchrony between the employed modalities
- the agent's gestures should look natural as humans are sensitive observers of each other's motion, in particular of motions supposed to convey meaning like gestures

Figure 1. A partial view on the articulated structure of our virtual agent comprising 59 joints including the hands.

Generating movements of a highly articulated figure is frequently based on low-level keyframing which, besides providing the most detailed and flexible control, causes the problem of controlling an excessive number of degrees of freedom (DOF) in a coordinated way. It seems natural to take into account findings from various fields relevant to the production and performance of gesture in humans, e.g., from psycholinguistics and motor control theory, in order to construe an appropriate method for generating and controlling the gestural movements of a synthetic humanoid. In this paper, we discuss results from related disciplines and, based on conclusions from this, present a hierarchical knowledge-based approach to the generation and animation of lifelike gestures of an articulated figure as shown in fig. 1. The presented model is conceived to drive the underlying kinematic skeleton of our virtual agent which comprises 43 DOF in 29 joints of the main body and 20 DOF in 15 joints of each hand.

2 Gesturing in Humans

In contrast to task-oriented movements like reaching or grasping, gestures are derived to a great extent from some kind of internal representation of "shape". Gestural movement exhibits characteristical shape and dynamical properties which enable humans to distinguish them from subsidiary movements and to recognize them as meaningful [6]. Kendon [5] points out that human gestures can be considered as composed of *gesture phrases*. These, in turn, consist of one or more movement phases, *preparation*, various *holds*, *stroke* (the most meaningful and mandatory part of the gesture phrase), and *retraction*, forming a hierarchical kinesic structure. According to McNeill [11], coverbal gestures are generated mostly unconsciously and closely related to speech flow yielding semantic, pragmatic, and temporal synchrony between the two modalities. DeRuiter [4] points out that the stroke onset covaries in time with the most contrastively stressed syllable in speech.

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Information processing models for the production of (coverbal) gesture are based on hybrid knowledge representations in a working memory, including propositional and imagistic information which are passed down to an abstract motor planning and control system. DeRuiter's model [4] provides a *conceptualizer* module that decides on what information is to be conveyed in gesture and at which time. Different types of information are expressed in different kinds of gestures, which are defined by a *sketch* encoding the relevant information. The sketch is passed down to lower levels, where the gestural movement is planned and executed. In the model of Krauss and Hadar [8], in contrast, gestures precede conceptualization and are assumed to be products of memory representations rather than of communicative intentions. The authors assume a separate module to be responsible for the selection of spatial and dynamical features out of the activated representations in memory, rendered as spatial/dynamic specifications of movements, and passed on to a motor planner. However, both models rely on rather vaguely defined subprocesses for the translation of information into motor programs for bodily movements.

Models of human motor control are commonly conceived in a hierarchical structure [14]. At the highest levels, the global aspects of the movement are represented in the form of an abstract goal. Control is passed down through progressively lower levels until all particular choices are made about which motor units to use. The higher levels in the system do not have any direct control over low-level motion generators, e.g. muscle contractions, but only over adjacent levels of control that eventually result in contractions. Control may even appear to reside at several levels simultaneously, with processes occuring in parallel at different levels [14]. Latash [9] proposes a general scheme of motor control that incorporates three levels which can be found in many other approaches. Planning voluntary movements is performed directly in terms of kinematics in the external Cartesian space rather than in complex "intrinsic" representations like joint rotation signals. Formation of arm trajectories is done on the basis of knowledge about the initial arm position and the target location. This suggests that primarily significant locations and postures are represented internally, and intermediate movements are generated by the motor control system automatically. Hence, planning of movement constitutes the *first step* of information processing, where the goal of the planned movement is expressed in terms of its trajectory. To this end, a motor control system should be able to perform an internal simulation of a movement and to generate a function that reflects the desired trajectory. The *second step* is to translate the simulated trajectory into motor variables which drive the lower structures. The resulting *virtual* trajectories partially encode certain properties of movement, including patterns of transition from an initial to a final position. In the *third step*, the execution of these commands at the lowest level leads to a movement that, in the ideal case, exactly follows the simulated trajectory.

3 Motion Generation of Synthetic Gesture

Most work concerning the *automatic* generation of lifelike gesture in virtual agents has been done in developing 2D presentational agents, e.g. André et al. [1]. These systems mainly focus on the formation and planning of multimodal presentations in certain discourse situations. However, the resulting utterances mostly include completely predefined, stereotyped gestures which are chosen from behavior databases. Similarly, the *Animated Conversation* system by Cassell et al. [2] focusses on the formation of communicative acts in given discourse situations, but provides a few heuristic rules for the generation and sychronization of gestures. Gestural movements are apparently predefined and parametrized in terms of alteration of single gesture phases, e.g. foreshortening the relaxation phase when the prerecorded "canonical" gesture time exceeds actual timing constraints, but there appears to be no means of coherently modifying the gestural movement while preserving natural movement features, e.g. typical velocity profiles. Perlin and Goldberg [12] created lifelike motions of virtual actors by means of script-based animations which are subject to rhythmic constraints and stochastic noise functions yielding a slight but permanently altered appearance. Gibet and Lebourque [10] present a sensori-motor model, restricted to a hand attached to a three-segment arm, that generates natural hand-arm movements on the basis of successive target end-points annotated with synchronization properties. Natural motion is achieved by heuristic knowledge, e.g., minimization of a cost function during inverse kinematics computation of arm postures and estimation of movement duration. The recent EMOTE model by Zhao et al. [3] emphasizes qualitative aspects of movement to increase naturalness of independently predefined human-like motions. Based on the Effort and Shape components of Laban Movement Analysis, operational models for expressive arm and torso movements provide an intuitive way of controlling the manner of movements, but not the movement itself.

In summary, all these systems produce movements which are only parametrizeable to some extent or fully rely on predefined motion sequences. While this approach proves sufficient for symbolic gestures like waving, it is clearly inadequate when it comes to the creation of context-dependent gestures like deictics or iconics, as well as to a careful synchronization and coordination with additional modalities. Instead, a flexible representation is needed specifying significant spatial and kinematic features of the gestures, their temporal relationships, as well as how to adjust them to the individual context of accompanying speech. The descriptions must serve as basis of planning the gestural movement with respect to its form, timing, and final execution. Such a comprehensive model for the automatic generation of gestures based on flexible symbolic descriptions of spatiotemporal features is still lacking.

4 A Model for the Animation of Lifelike Gesture

The general goal of our research is an operational model that enables convincing gesture animation from adequate representations of spatiotemporal gesture knowledge, filling the gap between models of gesture production and low-level motion control. To this end, it must provide means of motion planning performed in extrinsic representation, according to the *principle of smaller complexity*, and controlling the configurations of a highly articulated figure, as shown in fig. 1, which have eventually to be described intrinsically in joint angles. Furthermore, it must be flexible in the sense that gestures can be fully parametrized with respect to kinematics, i.e. velocity profile, overall duration, and stroke time, as well as to shape properties. The conceived model shown in fig. 2 incorporates two major stages, namely, "gesture planning" and "generation and execution of motor command" and provides all necessary computational steps from gesture planning to movement execution. This section describes the overall gesture generation process and provides a more detailed analysis of the planning steps.

4.1 Gesture Planner

Automatic motion generation usually starts by creating initial, final, and optional intermediate postures. The actual motion is then created

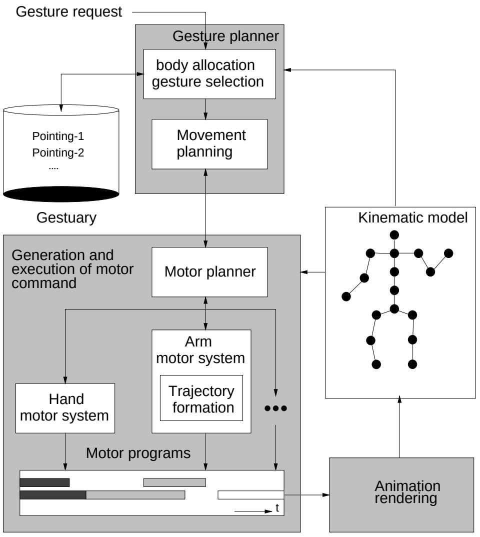

Figure 2. Overview of the proposed model of gesture animation.

by connecting postures in sequences. While it is unrealistic to assume final postures for a task-level goal in advance, we can revert to the definite spatiotemporal properties of the gesture, which provide postural and kinematic constraints during movement (see section 2). In the gesture planning stage, the mandatory spatial and dynamical features are translated into a trajectory in Cartesian workspace which meets the intended motor goal. This involves the creation of an image of the movement of the relevant limbs, formed by sequencing spatial features of the gesture. These are given either as spatiotemporal information from previous stages of gesture production, e.g. the location of the referent for deictic gesture or an outlined shape for iconic gestures, or they are retrieved from further representations of gesture knowledge, e.g. the conventionalized hand shape during pointing or the preferred ways of pointing [4]. Therefore, our model comprises a lexicon which contains feature-based descriptions of gestural movements along with information about their usage for transferring communicative intent (the *function* of the gesture) and is, following deRuiter, called *gestuary*. Hence, the gesture knowledge of the agent is defined by mappings from communicative content onto explicitly described movements.

4.1.1 Gestuary

In the gestuary, each gesture is described by an *abstract* frame-based template which contains, besides unique identifiers for the gesture and its function(s), mandatory features of the gesture stroke described in terms of movement constraints. These in turn define either postural features (*static* constraints) or significant movement phases (*dynamic* constraints) which have to be met as far as possible at lower motor levels. With regard to hand-arm gestures the template may contain slot-value pairs for *hand shape*, *hand orientation* (given by *palm orientation* for forearm twist and *extended finger orientation* for two rotational degrees of freedom in the wrist), *hand location* (in terms of the hand carpus which coincides with the root joint of the branched kinematic chain of the hand model), and *hand movement*. While certain invariant features can be defined independently using a symbolic gesture notation system, *HamNoSys* [13], others must be determined for each individual gesture. To this end, the description further accommodates entries which uniquely refer to specific values of the content the gesture is to convey, e.g. quantitative parameters for position or size.

In order to specify the overall gesture's course in time, temporal relationships between *simultaneous* and *subsequent* gesture features are represented qualitatively by a constraint tree using PARALLEL and SEQUENCE nodes, which can optionally be nested. A number of parameters are left unspecified in the gestuary, e.g. the exact hand location during pointing or the duration of the gesture, thus speaking of an *abstract* gesture template. Consider for example a deictic gesture: Our virtual agent is to convey the location $\overrightarrow{p}$ of an object from a certain direction $\overrightarrow{d}$ by gesture. An appropriate pointing gesture Pointing-1 with index finger streched fulfills the desired function Ref_To_Loc and is retrieved from the gestuary:

```
( MAPPING
   ( IDENT          Pointing-1)
   ( FUNCTION       Refer_To_Loc )
   ( CONSTRAINTS
      ( PARALLEL
            ( STATIC ( HandShape                 BSifinger))
            ( STATIC ( PalmOrientation           PalmD))
            ( STATIC ( ExtFingerOrientation      RefDir))
            ( STATIC ( HandLocation              RefLoc))
            ( STATIC ( HandMovement              MoveHalt))
      )
   )
)
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Yet, the pointing gesture definition, which already specifies three invariant features in symbolic *HamNoSys* descriptions (BSifinger, PalmD, MoveHalt; explanations given below), must be adjusted first by assigning parameter values to RefDir and RefLoc, derived from actual content ($\overrightarrow{p}$ and $\overrightarrow{d}$) and, second, applying optional external temporal constraints to the gesture stroke from which the times of validity of individual movement constraints can be determined. Such descriptions in the gestuary are the basis of gesture selection and movement planning described next.

4.1.2 Body Allocation and Gesture Selection

The gesture planner first has to decide which limb to use for the gesture. As this choice is partially resembled by the retrieval of a specific gesture template, the planner, first, collects all gestures from the gestuary which fulfill the required communicative function. Then, taking into account information from various sources like proprioceptive feedback or specific attributes of the actual gesture, the planner suggests a particular gesture template description, e.g. Pointing-1, which suits best the actual movement conditions.

4.1.3 Movement Planning

After succeeding in gesture selection, the gesture planner starts to plan the individual movement. Only the relevant spatiotemporal characteristics of the gesture *stroke* are planned at this stage. Positioning the limb in preparation of a stroke and moving it back to a rest position is generated by motor programs at a lower level.

The first step in movement planning is to complete the constraints in the gesture specification. To this end, concrete values for variant features are determined and inserted in appropriate slots. For instance, the features of the pointing gesture Pointing-1 are eventually determined as follows (*HamNoSys* symbols given in parentheses):

1. The hand shape is given by a separated index finger which is completely stretched while all other fingers are bent (d). The vector $\overrightarrow{f}$ denotes the position of the index finger tip with respect to the hand root joint (carpus).

2. The palm is oriented downwards (◒) and the extended finger orientation (the direction of the vector originating at the wrist, running along the back of the hand) is collinear to the target direction RefDir, bound to the vector $\overrightarrow{d}$.
3. The location of the hand carpus is such that the position of the index finger tip equals the target position, that is $\vec{p} - \vec{f}$ (referred to as RefLoc). Note that this relation holds for all hand pointing gestures, whether the index finger is completely stretched or not.
4. The hand movement halts simultaneously with the occurence of the other features (‖).

Next, the planner applies possible external temporal constraints, like stroke onset and duration due to cross-modal synchronization and schedules the gesture stroke appropriately. To this end, each movement constraint can be assigned a start and end time during which the constraint needs to be satisfied by the resulting motion. This is done by traversing the tree structure of the gesture specification (see 4.1.1) which prescribes qualitatively the general temporal relationships between single movement constraints. Children of a PARALLEL node are always assigned the same start and end time, while children of a SEQUENCE node are ordered consecutively.

A complete timing definition of all movement constraints, of course, cannot be determined solely from overall stroke timing. Instead, the stroke timing is restricted to necessary synchrony constraints concerning mainly the stroke *onset*. Furthermore, optional movements which have to be executed in preparation of satisfying a certain constraint are not planned explicitly at this stage. As these movement phases influence the temporal structure of the resulting gesture, the movement's timing may be refined at lower levels. Therefore, start and end times of individual constraints are ranked using numerical values between zero and one, defining a level of commitment for the underlying motor system. Timing constraints which can be qualified firmly at this stage are assigned maximum value while uncertain times are left variable. In fig. 3 a movement plan for a grasping gesture is shown which is scheduled to be performed within 1.2 seconds. Time points that cannot be stated definitely from overall stroke timing and hence may still be subject to variations are assigned a commitment value of zero.

In summary, the gesture planner forms a movement plan, i.e. a tree representation of a temporally ordered set of movements constraints, by (1) retrieving a feature-based gesture specification from the gestuary, (2) adapting it to the individual gesture context, and (3) qualifying the movement constraints to the extent possible by applying external temporal constraints.

4.2 Generation and Execution of Motor Command

As human movements and in particular gestures exhibit typical movement patterns, we adopt the concept of *motor programs* [17] which encapsulate control patterns of motion variables, i.e. joint angle values. To this end, motion control is decomposed in the *motor planner* into more simple modules to overcome the problem of driving the excessive DOF of highly articulated structures.

4.2.1 Motor Planning

Distribution of motion control among specialized motor systems is done by distinguishing movement constraints according to the affected body parts. Currently, control of hand and arm movements are separated in our system. While relying on the independence between both motor systems, it is crucial to guarantee synchronization at discrete time points. This is assured by previous integrated movement planning and by ordering related constraints in lists, preserving their temporal relationships. The resulting constraint sets are passed down to dedicated motor subsystems which in turn generate appropriate motor programs for the execution of each submovement. The movement plan of the grasping gesture (fig. 3) is converted into constraint lists as shown in fig. 4.

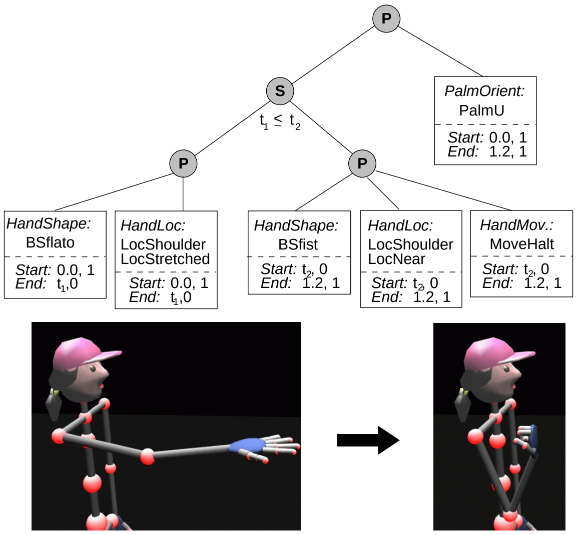

Figure 3. Hierarchical movement plan for a grasping gesture.

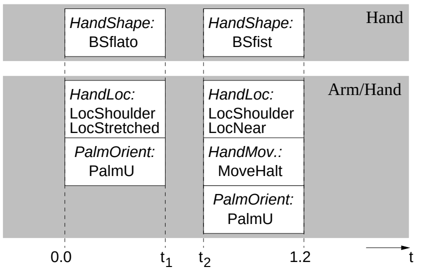

Figure 4. Motion generation is decomposed by creating independent temporally ordered constraint lists.

In case the preplanned timing of a movement constraint cannot be satisfied by a motor subsystem (e.g. due to extensive transitional movements), achievable start and end times for the corresponding constraint are generated and integrated with all temporally related movement constraints to preserve the gesture's temporal structure. Hence, replanning of the movement becomes necessary and the gesture generation process returns to the movement planner which tries to resolve the temporal constraints. The resulting movement is hence re-scheduled due to *co-articulation* effects.

In our current system, hand motion is controlled solely by a specialized hand model which interprets *HamNoSys* descriptions of hand shape by translating them directly into hand poses and applies stereotyped transitions between them. In contrast, alterations of hand location and orientation are caused by arm movements. Thus, constraints concerning such features of the gesture are transferred to an arm control module, which translates *HamNoSys* symbols as well as numerical values into position and orientation constraints with respect to the *egocentric* frame of reference. Then, a trajectory is formed which satisfies all imposed spatiotemporal constraints, smoothly connected with lifelike preparation and retraction movements.

4.2.2 Trajectory Formation

In this phase, a arm trajectory is created which connects single events with boundary conditions retrieved from feedback information about current movements. Taking the target positions and orientations as input, the trajectory is generated by, first, either retrieving a start position by traversing the kinematic model or taking into account currently executed motor programs. The resulting position and velocity gives the initial event of the limb's trajectory at *planning time*. Then, a stereotyped retraction movement is appended as observed in experiments [15], which report slight overshooting before coming to rest. To eventually form a lifelike trajectory, findings from motor control theory [9] are taken into account. First, external coordinates appear to be the superior representation in human movement planning which suggests trajectory formation in Cartesian coordinates. As spatiotemporal gesture features are given at distinct times, this leads to an interpolation problem for effector joint trajectories. This is reasonable as joint angle interpolation is by no means guaranteed to produce natural trajectories in external coordinates due to the non-linear mapping between both spaces. Second, movement shape is to some extent invariant from overall movement duration and there is likely a simple scaling for permitting the same movement at different speeds in humans [9]. Finally, more complex movements consist of elementary units glued together, and relative movement speed drops at the points of connection of the motor primitives, which frequently correspond to points of maximal trajectory curvature.

Therefore, we employ two independent nonuniform cubic B-spline interpolants, the "position curve" defining the movement's trajectory in space, and the "velocity curve" expressing arclength against time. We do not go into detail here as to how position and velocity curves are achieved in particular [7]. Once trajectory formation is completed, a motor program is created and fed into the central animation queue (see fig. 2). As all motor programs in the queue are (de-)activated depending on their predefined start and end time with respect to the agent's internal *wall-clock* time, the planned submovement is executed by the motor program in a strictly timed manner.

4.2.3 Rendering Animations from Motor Programs

An arbitrary number of independent motor programs may be simultaneously active which are, once activated, executed concurrently. While motor programs created by the hand motor system directly affect the kinematic model by modifying joint angles, arm movements are defined in terms of trajectories in Cartesian coordinates which are reparametrized in arclength to control the movement's velocity using standard techniques [16]. Then, for each incrementally altered limb position the inherently ill-posed inverse kinematics problem is solved in real-time by an extension of the Jacobian Transpose method [7]. Our algorithm tracks the position curve of the end-effector of arbitrary kinematic chains while taking into account restrictions of the human body and additional biomechanical heuristics. Once a motor program is completed, it is removed from the animation queue and the according movement comes to halt.

5 Summary

In this paper we have presented a comprehensive knowledge-based approach for animating gestures of an anthropomorphic agent, based on relevant findings in related disciplines. The developed methods for feature-based movement representation and planning provide the flexibility to compose gestural movements which satisfy the requirements stated in the introduction. All movements can be adjusted to the actual gesture context as well as to temporal synchronization constraints. The lifelikeness of the virtual agent is further increased by reproducing human movement characteristics and co-articulation effects. As far as we can see, none of the proposed routines includes methods that lead into computational complexity preventing execution of gesture in real time. An experimental implementation of the model includes the animation rendering parts, the hand motor system, as well as the gesture planning module; the arm motor control is currently under development. Our mid-range goals include the integration of text-to-speech and speech-synthesis techniques as well as run-time extraction of temporal constraints for the control and coordination of gesture and speech.

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