Inverse Kinetics
for Center of Mass Position Control
and Posture Optimization

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Abstract

The range of Inverse Kinematics has been extended by integrating the mass distribution information to embody the control of the position of the center of gravity of any articulated figure in single support (open tree structure). The underlying control architecture of main and secondary behaviors (or tasks) is used to associate the position control of the center of gravity with other behaviors. The combined quality of providing realistic postures in real-time improves significantly the potential interaction with human model in virtual reality applications and more generally for real-time video productions.

1 Introduction

In this paper we focus on interactive design of realistic postures in the sense of static analysis. Our approach only requires the topological, geometrical, and mass distribution information of the articulated figure. The range of Inverse Kinematics has been extended by integrating the mass distribution information to embody the control of the position of the center of gravity of any articulated figure in single support (open tree structure). The framework of Direct and Inverse Kinematics is still valid in this new context because it expresses the resulting combination of kinematics and mass distribution; we therefore refer to it as *Direct and Inverse Kinetics* . The underlying control architecture of main and secondary tasks (or behaviors) is used to associate the position control of the center of gravity with other optimization behaviors. We have focused on realistic balance behaviors while ensuring fast response thus allowing integration in virtual reality applications and more generally for real-time video productions.

First, we analyze the state of the art in the balance control of an articulated figure and stress the incomplete use of the mass distribution information. Then, we recall the basic concepts of inverse kinematic control, its strengths and weaknesses. The next section introduces how we can use the mass distribution information to evaluate the kinetic influence of any joint of the articulated figure. Our kinetic control is then combined with optimization behaviors regarding the balance of an articulated figure. The next section present the cascaded control scheme, which allows the hierarchical combination of various behaviors. The paper ends with various 2D examples and one 3D illustration with an emphasis on posture optimizations.

2 Background

2.1 Review

In [1] [2] and [3], the human balance control is one aspect of the design and analysis of body posture by mean of kinematic constraints and behavioral functions. Their approach to control the position of the center of mass is completely described in [2]. For these authors, the center of mass is considered as an end effector attached to the lower torso region. It is controlled by inverse kinematics with the ankle, knee, and hip joints of the dominant leg (the one supporting most of the weight) as the constraint variables. This approach has proven to be effective in managing the position of the center of mass but some aspects make its use rather limited and its background kinetically unrealistic. First, it is very specific to the human standing posture, which means that we cannot generalize it for any arbitrary articulated figure and even for a human structure with a different support or attach (hanging by the hands, sitting or else). Second, the kinetic influence of the joint variables is not evaluated with respect to the mass distribution in the whole body.

Although not directly focusing on the position control of the center of mass, the work of Lee [4] belongs to the same research stream as it tries to identify a comfort model integrating the human strength information in order to realistically perform some reaching task. As such, it should be able to improve the understanding of posture control for general reach tasks. Unfortunately, due to a lack of strength data for other joints, the model is limited to the upper body and especially the arm chain, from the shoulder to the hand[4]. The validation is limited to a comparison of the path obtained by the simulation with the measurements obtained from NASA experiments for three reach tasks without loads. It is difficult to assess the validity of this approach only from geometric data ; one would have expected the values of the joint torques over time, at least from the simulation. Other approaches [5], [6], [7] have also considered the control of the center of mass. The system presented in [6], dedicated to bipedal walking, is mostly kinematic but also includes some dynamic rules so as to maintain the center of mass within the support polygon. A similar approach [5] has defined kinematic and dynamic rules so as to partially control the balance via the position of the center of mass, and to minimize the effort developed by the muscles. The approach is applied to optimize various motions such as walking, sitting on a chair and climbing stairs. Despite the fact that this author can successfully manage the balance in the case of sitting (and especially, getting up from a seat), the control of the center of mass is actuated only with the bending of the torso, which limits its range of application.

Dynamic control of articulated figures has been proposed to produce physically realistic postures and animation [8] [9]. A recent approach [8] provides a control algorithm to generate realistic running and jumping motions. Such motions present a ballistic phase and at most a single support phase. As the authors themselves state, the control of double support phases, as in walking, is still very difficult to handle [10]. This is due to the requirement to manage the ground reaction force in order to perform a realistic motion. On the other hand, the results presented in [9] concentrate on statically stable multi-legged walking. There are always more than two legs supporting the articulated character so that the center of gravity generally lies in the sustentation polygon. In such a context the balance control is a less important issue than the coordination of the legs. Optimal control is a promising approach for natural postures and animation design [11] [12] [13] but it still faces severe limitations in terms of calculation cost.

2.2 Discussion

Physically realistic approaches, as dynamic or optimal control are not yet suited for interactive design of human postures due to the difficult handling of their associated parameter space (torque, muscle activation) or the additional parameter added by the control approach (energy storage, management of the ground reaction force). They are not intuitive and easy to handle for an animator as stated in [8]. Moreover, a higher level approach based on a human comfort model still faces severe lack of data for realistic strengths[4]. Finally, regarding optimal control, its major limitation comes from the high dimension of the human figure (*e.g.* 88 degrees of freedom in [2]) preventing real-time interaction on current workstations.

Conversely, Inverse Kinematics lacks physically based guarantees which limits its application either to interactive postural design and optimization or to motions with negligible dynamics (slow speed with minimal frictional and inertial effects [2]). This approach is rather successful within this context and especially by means of behavioral control [3], but we have quoted serious problems related to the control of the center of gravity which can reduce the validity of postures resulting from balance behaviors. Although the strength-based approach of Lee is very stimulating it does not address the position control of the center of gravity ; moreover it has not yet been validated. An equally important shortcoming of inverse kinematics, especially for redundant mechanisms, is its intrinsic property of providing a local solution without any means of knowing whether other solutions exist [14]. The optimization of a secondary criteria has been widely used in robotics to improve that aspect [15],[16],[17] but still there is no guarantee of avoiding local minima. Moreover, the analyzis of the unrealistic demands on mechanism performance induced by the use of the secondary task is clearly developed in [17].

For these reasons, we propose an extension of Inverse Kinematics which takes into account the mass distribution of the whole body, resulting in a new control metaphor we call Inverse Kinetics. Our approach is completed with optimization behaviors which allow a coherent and kinetically realistic management of postures with single support in the sense of static analysis. An important remark regarding joint strengths is the fact that we are mainly concerned by the optimization of postures while maintaining the balance of the articulated model and without carrying additional payload. In that context, we assume that the joint torques remain in the range of their allowable strength.

3 Inverse Kinematics

As stated before, Inverse Kinematics is a technique mostly used to control or constraint strategic parts of the articulated figure, whose location depends on a set of parameters, usually joints values. The associated control scheme is based on a linearization of this problem at the current state of the system. Consequently, its validity is limited to the neighborhood of the current state and, as such, any desired motion has to comply with the hypothesis of small movements. The discrete form of the general solution provided by inverse kinematics is:

$$\Delta q = J^{+}\Delta x + (I - J^{+}J)\Delta z \qquad (1)$$

where

? q is the unknown vector in the joint variation space, of dimension **n**.

? x describes the so-called *main behavior* as a variation of one or more end effector(s) position and/or orientation in Cartesian space. Its dimension, noted **m**, is usually less than or equal to **n**, to be of interest for inverse kinematic control.

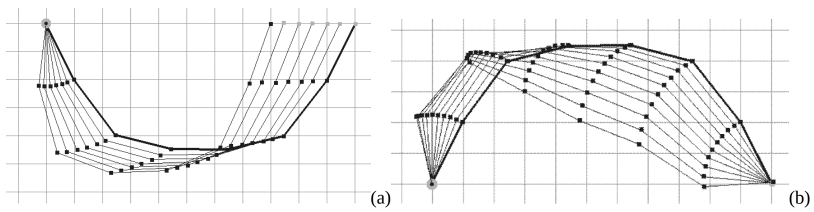


Figure 1 : Inverse kinematic control : (a) minimal norm solution for a desired translation (b) solution belonging to the kernel of the joint variation space

J is the Jacobian matrix of the linear transformation representing the differential behavior of the controlled system over the dimensions specified by the *main behavior* (figure 2).

$\mathbf{J}^{+}$ is the unique pseudo-inverse of **J** providing the minimum norm solution which achieves the *main behavior* (figure 1a & 2).

I is the identity matrix of the joint variation space (**n** x **n**)

$(\mathbf{I}-\mathbf{J}^{+}\mathbf{J})$ is a projection operator on the *null space* of the linear transformation **J**. Any element belonging to this joint variation sub-space is mapped by **J** into the null vector in the Cartesian variation space (figure 1b & 2).

?z describes a *secondary behavior* in the joint variation space. It is partially realized by the projection on the *null space*. The second part the of equation does not modify the achievement of the main behavior for any value of **?z.**

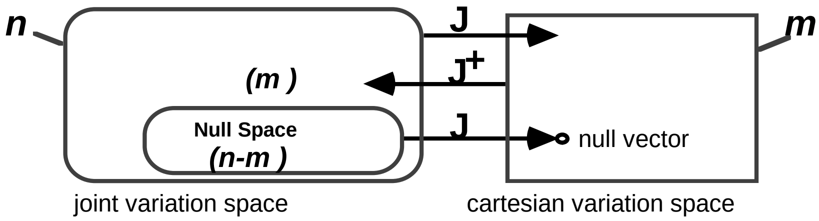


Figure 2 : Illustration of the joint variation space partitioning with Inverse Kinematics

Three characteristics of Inverse Kinematics are fundamental for the understanding of our approach. First, this methods provides a local solution [14]. For example, given a goal to reach with an end effector, the final posture of the articulated figure depends on the initial configuration. Other solutions, if they exist, cannot be evaluated ; they can only be guessed from the dimension of the null space. Second, the secondary behavior should express the minimization of a cost function. If the main behavior belongs to the image space of **J** then the null space is (**n-m**) dimensional in the joint variation space. From this information we can deduce to what extent the secondary behavior may be fulfilled, or rather, may not be fulfilled. In the context of our study, we are interested in optimizing the posture with respect to balance and partially to effort cost. Based on these guidelines, we will use the mass distribution of the articulated figure to evaluate associated pertinent cost functions. Third, the configuration may become singular. This situation is due to an alignment of the segments constituting the articulated figure leading to a loss of mobility of the effector(s) in that direction. The Jacobian has a loss of rank or, even worse, a very small singular value along that Cartesian dimension inducing by inversion a solution norm growing to infinity when a behavior is required in that direction. We use an elegant solution to this problem called the damped least square and described in [18] where the norm of the solution is limited near the singular cases.

4 Direct and Inverse Kinetics

Section 2 has reviewed different approaches related to the control of the center of mass and we have stressed a real need for a general and consistent method suited for such control. The basic principle of our approach is to evaluate the kinetic influence of the joints based on the fraction of the total body mass they support, *i.e.* their augmented body. More precisely, the augmented body associated with a joint is the imaginary rigid body which is supported by this joint at the current state of the system. Figure 3a shows the center of mass of all the augmented bodies of a fern crozier while figure 3b illustrates the augmented body associated with one joint.

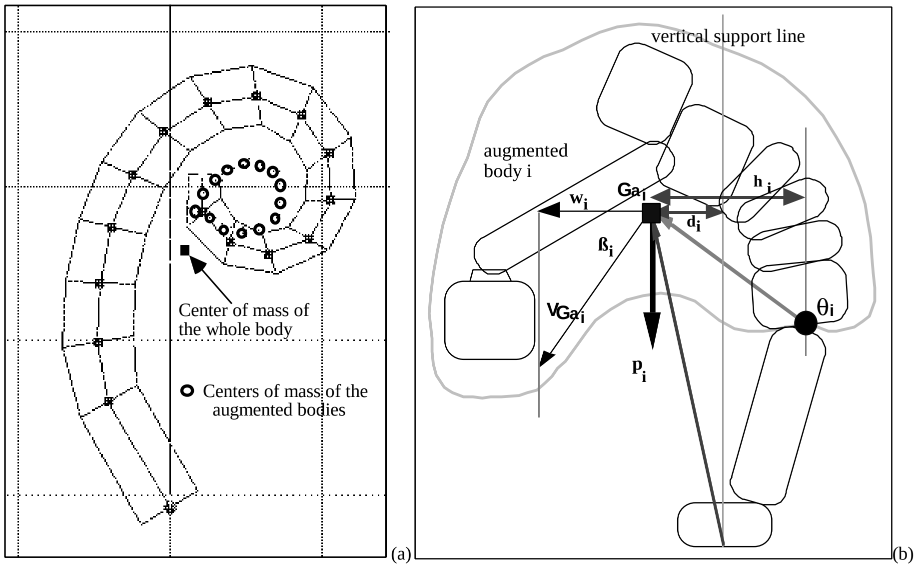


Figure 3: (a) centers of mass of the augmented bodies for one posture of a fern crozier
(b) concepts and variables used in Inverse Kinetics and balance optimization

Our method consists first in evaluating the kinetic influence of the joints by relating instantaneous joints variations with the corresponding instantaneous translation of the total center of mass (Direct Kinetics). In a second stage the matrix of the resulting linear transformation is inverted in a process similar to Inverse Kinematics. However, since it integrates the mass distribution information, we call it Inverse Kinetics.

Let **q** be the parameter vector of an open articulated chain made of **n** elementary bodies. Each elementary body **i** has a mass $\mathbf{m_i}$, a local origin $\mathbf{O_i}$ and a local center of gravity $\mathbf{G_i}$. For the sake of clarity, the origin $\mathbf{O_1}$ is located on the origin of the reference frame $\mathbf{S_o}$. The position of the center of gravity **G** of the whole chain, with a total mass **m**, is given by the following formula:

$$O_1G = \frac{1}{m}\sum_{i=1}^{n} m_i O_1 G_i \qquad (2)$$

We now introduce the intermediate links between O_1 and the G_i :

$$O_1G = \frac{1}{m}\sum_{i=1}^{n} m_i \left(\sum_{k=1}^{i-1}(O_k O_{k+1}) + O_i G_i\right) \qquad (3)$$

By differentiating with respect to time, we get the instantaneous translation vector of the center of gravity $\mathbf{V_G}$ expressed in frame $\mathbf{S_o}$ **:**

$$V_G = \frac{1}{m}\sum_{i=1}^{n} m_i \left(\sum_{k=1}^{i-1}\left(\left[\frac{dO_k O_{k+1}}{dt}\right]_{S_o}\right) + \left[\frac{dO_i G_i}{dt}\right]_{S_o}\right)$$

Each vector first derivative with respect to time can be expressed as a function of the instantaneous rotation vector $\mathbf{w_j}$ due to the variation of parameter $\mathbf{q_j}$, noted $\mathbf{q'_j}$, along the normalized vector $\mathbf{r_j}$: $w_j = q'_j r_j$ (4)

$$V_G = \frac{1}{m}\sum_{j=1}^{n} w_j \times \left(\sum_{i=j}^{n} m_i O_j G_i\right) \qquad (5)$$

We can now introduce the position of the center of gravity $\mathbf{G_{aj}}$ of the augmented body (of mass $\mathbf{m_{aj}}$) associated with the parameter θ_j. The augmented body is the instantaneous rigid body composed of all the elementary bodies supported by the joint **j**. Again we have :

$$O_j G_{aj} = \frac{1}{m_{aj}} \left(\sum_{i=j}^{n} m_i O_j G_i\right) \qquad (6)$$

So, using (4) and (6), (5) becomes :

$$V_G = \sum_{j=1}^{n} \left[\frac{m_{aj}}{m} \left(r_j \times O_j G_{aj} \right) \right] q'_j \qquad (7)$$

and finally: $$V_G = [J_G] q' \qquad (8)$$

where $[J_G]$ is the Jacobian matrix weighted by the mass ratio of the augmented bodies to the total body, relating instantaneous translation of the center of mass to the instantaneous variations on the parameters. Conversely, the pseudo-inverse of this Jacobian matrix can be evaluated, allowing to provide an instantaneous variation of the parameters related to a desired instantaneous translation of the center of mass. In that sense it is correct to propose terms of Direct and Inverse Kinetics because it extends significantly the range of Direct and Inverse Kinematics for the control of articulated structures. We can also apply the principle of conservation of momentum on the augmented bodies center of gravity to demonstrate the direct kinetics fundamental relationship [19].

5 Posture Optimization Behaviors

We present here two methods of posture optimization. The first one focuses on the minimization of moments with respect to the center of support (support torques) while the second tries to identify and minimize the torques exerted in the standing rest posture. Both use information related to the center of mass of the augmented bodies. As we are able to express their minimization in the joint variation space, they are suited as secondary behaviors in Inverse Kinematics or Inverse Kinetics.

The support torques tend to rotate the whole body around the center of support under the influence of gravity. We minimize the following cost function $\mathbf{C_S}$ expressing that every independent support torque $\mathbf{T_i}$, should be geared to zero rather than their algebraic sum alone:

$$C_S = \sum_{i=1}^{n} \left\| T_i \right\|^2 \qquad (9)$$

The relation between cost function C_S and the joints must be established in order to express its gradient vector in term of joint variations. Figure 3b illustrates the different elements entering this relationship for the augmented body associated with joint **i**. First, its support moment comes from the action of the weight $\mathbf{p_i}$ and is directly proportional to the distance $\mathbf{d_i}$ between $\mathbf{G_{ai}}$ and the vertical support line. Minimizing M_i is equivalent to minimize d_i . Now, the influence of a joint variation on d_i can be deduced from its influence V_{Gai} on point G_{ai} projected on the axis supporting distance d_i (noted W_i). The resulting term of the gradient vector is proportional to :

$$\Delta Z_{S_i} = -2 \cdot m_{ai} \cdot d_i \cdot \|W_i\| \qquad (10)$$

The global minimum of this cost function is the configuration sub-space where the centers of gravity of all the augmented bodies lye on the vertical line of support.

The rest posture is a useful concept for the posture optimization of complex mechanisms presenting an active behavior (here for animals and human models). We consider it as the global minimum among standing postures regarding muscular cost (see [19] for justification). For this reason, we now propose a cost function converging to the rest posture and based on kinetic information. Although the minimization of the configuration interval to the rest posture clearly leads to the rest posture θ_r , it does not convey kinetic information and therefore has a low validity to express an effort cost. For this reason, a second factor representing such effort scales this cost function. We have retained the torque exerted by the augmented body weight with respect to the origin $\mathbf{O_i}$ of the joint rotation axis. Figure 3b illustrates the quantity $\mathbf{h_i}$ directly influencing the effort torque for joint **i**. Finally, the gradient term retained for the effort minimization is proportional to :

$$\Delta Z_{E_i} = -2 \cdot m_{ai} \cdot h_i \cdot (q_i - q_{ri}) \qquad (11)$$

Some gradient terms can be locally null whenever their effort torque vanishes due to the vertical alignment of the G_{ai} and O_i . By construction, they all vanish only for the rest posture.

Combining the two previous optimization behaviors is possible and even desirable to obtain the best compromise over the null space resulting from inverse kinematic or inverse kinetic control. Next section even introduces a third approach of posture optimization which can also be combined with the two presented here.

6 Integrated Kinetic and Kinematic Control

Kinetic and Kinematic control schemes share one common space, i.e. the joint variation space, hence allowing their integration into more sophisticated architecture as developed below. The control architecture presented now were paradoxically designed to overcome the optimal nature of the support moment minimization presented in section 5. This optimization minimizes each support moment independently which is not always desirable. For example, if we want to reach a distant target with the hand without moving the feet, it is necessary to allow lower augmented bodies to lean backward so as to counter-balance the forward leaning of upper augmented bodies containing the hand. Such a case is equivalent to ensure the algebraic sum of support moment to be null, *i.e.* to maintain the total center of mass on the vertical line of support. This sub-optimal approach has been identified in [2] but not treated kinetically. This is the purpose of this section.

We have shown in section 4 how to control the position of the center of gravity. It is now straightforward to integrate it as a secondary behavior of a classic kinematic control. In discrete form, we get the following cascaded architecture :

$$\Delta q = J_e^+ \Delta x_e + (I - J_e^+ J_e)(J_G^+ \Delta x_G + (I - J_G^+ J_G)\Delta z_o) \qquad (12)$$

Where J_e is the Jacobian of the kinematic transformation describing the effector control (for example a reach behavior), J_G is the Jacobian of the kinetic transformation describing the center of gravity control (balance behavior). Here the optimization behavior ? z_o is integrated through a second partitioning level of the joint variation space. It could also directly share the kinematic null space with the kinetic control. Moreover, the underlying hierarchy of expression (12) can be inverted to favor the center of mass control over the reach behavior :

$$\Delta q = J_G^+ \Delta x_G + (I - J_G^+ J_G)(J_e^+ \Delta x_e + (I - J_e^+ J_e)\Delta z_o) \qquad (13)$$

7 Simulation Results

Our approach is better illustrated with 2D models in order to visualize unambiguously the position control of the center of gravity. However, our method can be used for general tree-structured 3D articulated chains in single support as we show in the last example. Our goal is to show that we can achieve realistic results only with a mass distribution of the model. Such data can be derived as a first approximation from a volume distribution or identified roughly from multiple views. Conversely, it is very difficult to find data on more elaborate quantities as strengths and general joint modeling as required by other approaches. Whenever possible the simulation results are compared with real postures obtained from images.

The 2D representation of the articulated structures reflects the mass distribution in the following way: a segment $\mathbf{S_i}$ is defined between joint **i** and joint **i+1**. It has a length $\mathbf{L_i}$ and a mass $\mathbf{m_i}$; its width $\mathbf{l_i}$ is only displayed at the end-effector side of the segment and its value is proportional to ($\mathbf{m_i}$ **/** $\mathbf{L_i}$). In such a way the final display shows a continuous envelop if all the joint angles belong to the interval plus or minus p/2. Otherwise the sides of the envelop switch as can be noticed at the shoulder of the 2D human model (Figure 8).

7.1 The Fern Crozier

The fern crozier simulations highlight two points: first the interest of minimizing the support moments and second the precise position control of inverse kinetics on the center of mass. Although there is no explicit specification to unroll the fern crozier, this motion implicitly derives from the support moment minimization (Figure 4). Here, the center of gravity is pushed upward from the combined opening and closing variations of the augmented bodies in order to align their center of gravity on the vertical line of support. One can also notice that is slightly swaying along the vertical line of support. This characteristics also appear on the evolution of the support and the "joint" torques while globally decreasing to zero [19].

On the other hand, the Inverse Kinetics algorithm directly acts on the position of the center of gravity in Cartesian space. In Figure 5, it is interactively moved upward along the vertical line of support. As such the resulting postures strictly express the balance of the two parts of the fern between the two sides of the vertical line of support. The unrolling derives from the upward variation of position of the center of gravity by definition of Inverse Kinetics. The postures bear much less similarity with natural specimen. However, the simulation duration is much smaller (around 10%) than the one required for the minimization process to achieve the same decrease of torque amplitude (75% of the initial envelope amplitude) [19].

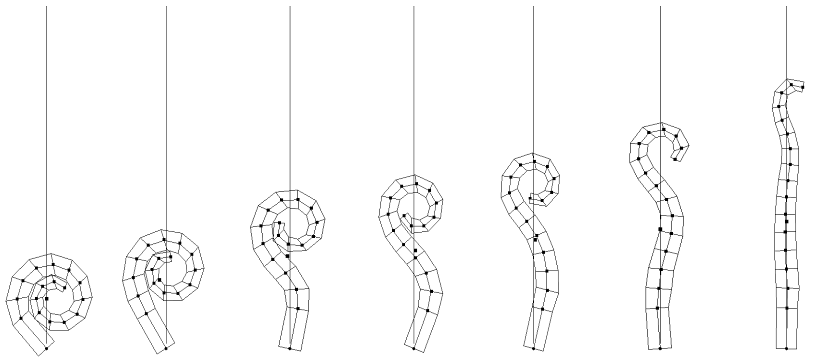


Figure 4 : Unrolling of a fern crozier with a minimization of the support moments

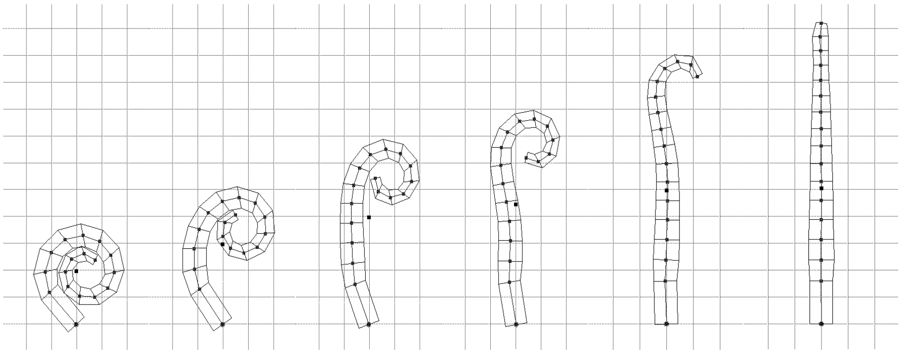
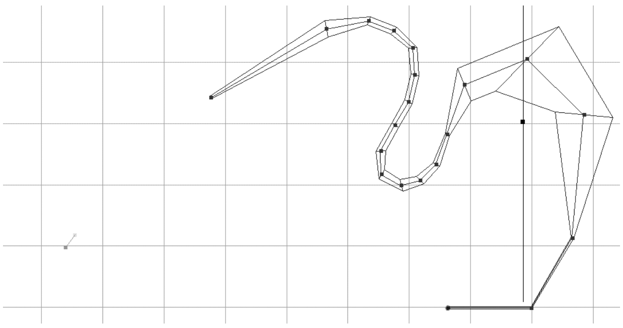


Figure 5 : Interactively unrolling a fern crozier with inverse kinetics

With this example we could also identify the center of gravity's reachable area in a straightforward manner. By construction Inverse Kinetics controls the position of the center of mass, so it just requires to span the Cartesian space and to draw the outer limit of the center of mass's excursion. As we know, the final configuration of the chain depends on the initial configuration. So the center of gravity's reachable area can be different depending on the initial configuration and the joint limits. It is important to associate independent reachable areas with their configuration sub-space

7.2 The Mallard Bird

The bird example is of great interest due to some radiographs (see p 79 in [20]) which have been used to identify the initial rest posture of the bird and to validate the posture predicted with cascaded control. Three of the body segments are rigidly connected for this reach simulation. Their purpose is to adjust the mass distribution so that the center of mass projection lies just in front of the "palm" joint in the rest posture .



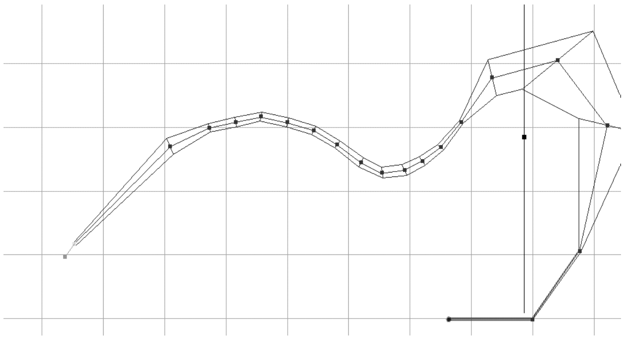


Figure 7 : initial and final stages of the Mallard bird maintaining its balance while reaching a water bowl (the top posture is considered as the rest posture of the subject)

The cascaded control of inverse kinematics with inverse kinetics is used to ensure a reaching and orienting task of the beak as main behavior while maintaining the balance of the subject as secondary behavior. Figure 7 shows the initial and final stages of the reach behavior simulation. Some other tests have even adjusted the mass distribution of the final posture to match the additional water distribution in the lower neck and the algorithm still stabilized close to the real posture. In the context of the present case-study the major differences with other control architecture is either the realism of the final posture or a much faster convergence of the cascaded control (around 10% duration, see [19]).

7.3 Human Posture Optimization

The human skeleton chain includes eight degrees of freedom. We can recognize, from floor level to hand, the toe, ankle, knee, hip, lumbar and thoracic spine, shoulder and elbow joints. In order to ease the correspondence with the 3D human skeleton, the lower limb segments have a double mass (foot, shank and thigh segments) and higher body segments integrate the mass of other body parts :

- the thorax segment includes the head and one arm mass
- the forearm segment includes the hand mass .

The projected center of gravity should be in the so-called *support polygon* made by the foot (or feet) between the ankle and toe joints. It should always remain in that space to maintain the balance of the whole body. When the toe joint is fixed the so-called *vertical line of support* is passing through the center of support located a few centimeters in front of the ankle joint. The first simulation consists in rising up from a squat posture with pure Inverse Kinetics.

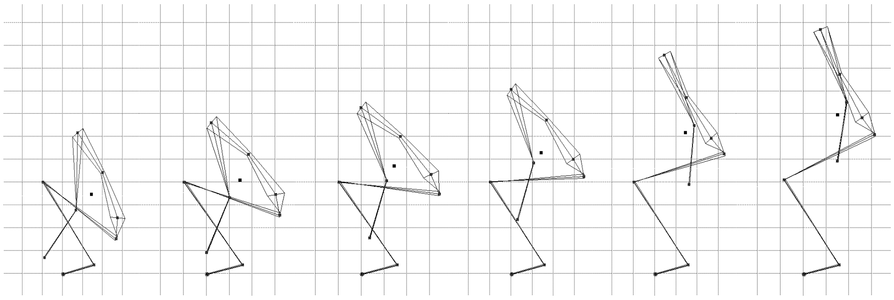


Figure 8 : partial sequence of a rising behavior from a squat posture (fixed toe joint)

For Figure 8, the toe joint is maintained fixed thus ensuring a constant support polygon. The evolution of the simulation is easier to read as the vertical line of support is constant. The center of mass is interactively controlled by inverse kinetics to move upward along the line of support. Figure 8 focuses on the first half of the motion. The overall minimization of the support and joint torques is ensured during the motion (see [19]). Such result validates the full erect posture as the best candidate for the standing rest posture among all the semi-erect postures.

The toe joint is allowed to vary in Figure 9. This new context raises the question of the support center location as a function of the toe flexion angle. Now, the support polygon is changing and the center of support is migrating from its rest location to the toe location as a function of the toe flexion angle. A dedicated function has been defined to model that phenomenon.

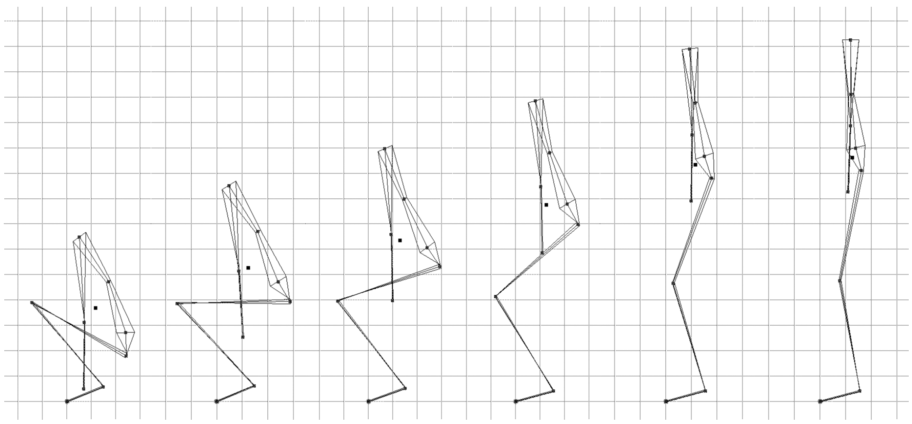


Figure 9 : partial sequence of a rising behavior from a squat posture (free toe joint)

The leftmost posture of Figure 9 has been obtained with a reach behavior to a floor location for the wrist (starting from the standing posture). One can notice the characteristic raising of the heel. The cascaded control equation is used with Inverse kinematics to guide the wrist position as the main behavior while maintaining the balance with Inverse Kinetics as the secondary behavior.

Figure 10 illustrate the use of Inverse Kinetics in a 3D context. The general tree structured human model is rooted at the right foot. The final posture shown here is also obtained by cascaded control with the reach behavior as the main task and the balance behavior as the secondary task. One can observe a significant bending of the lumbar vertebrae. We plan to evaluate more precisely the strain of the lower back due to this kind of posture.

8 Conclusion

In this paper we have intentionally focused on the presentation of the technical and fundamental aspects of inverse Kinetics to provide a broad view of its potentialities. Such technique has two important application fields :

First, Computer Animation for interactive control of articulated figure. Its purpose is to help the design of kinetically realistic postures in the sense of static analysis.

Second, Analysis of real images to enhance the identification and tracking of articulated figure postures. Our approach should improve the convergence of posture recognition by making some assumption on the position of the center of gravity (under the hypothesis of negligible dynamics).

Two major arguments advocate for the use of our approach for real and synthetic image processing. First, the mass distribution is a very intuitive set of parameters; it does not add the cognitive burden of the additional parameter space appearing in Dynamics for example. Once the mass distribution is set, the control is as intuitive as Inverse Kinematics. Our approach fits into existing high level interface of behavioral control of human figure; it brings the necessary realism for static positioning according to the mass distribution of the figure. Second, the calculation cost is comparable with Inverse Kinematics, hence allowing true interactive design of postures. One step further, it allows more convincing interaction of any articulated models with real subjects in the context of Virtual reality.

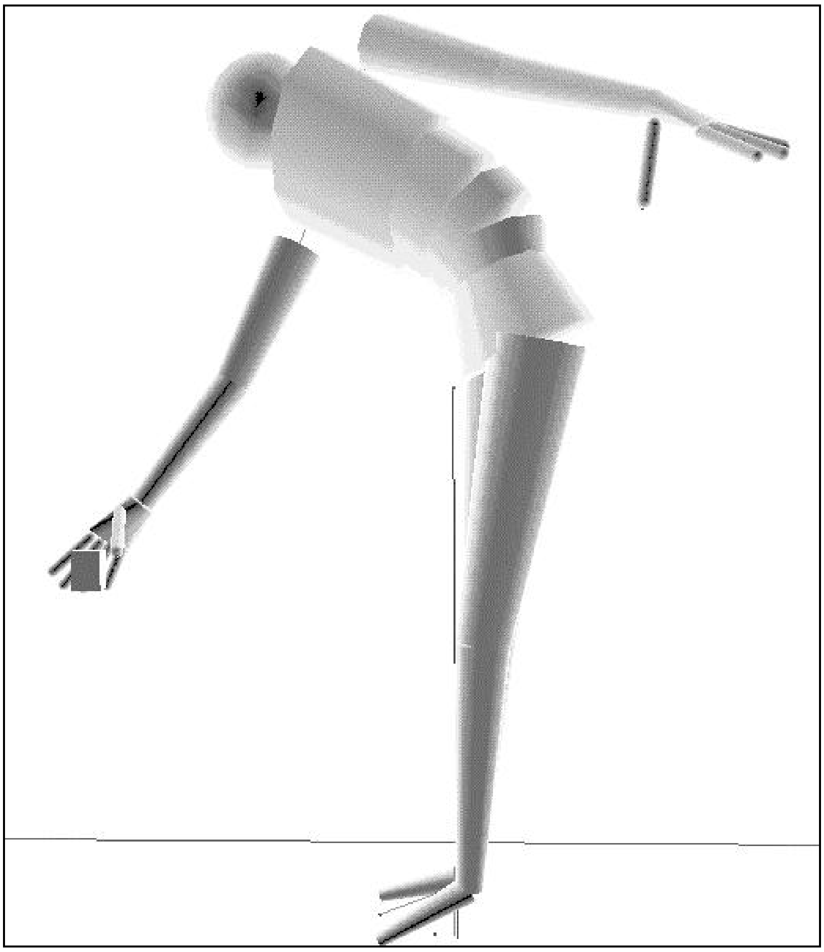


Figure 10 : 3D human model posture optimization (in single support)

9 Acknowledgments

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