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Control of an Iguana Character Using Soft-Body Simulation

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ABSTRACT The locomotion of lizards is characterized by lateral bending of the body, which is distinct from quadrupedal mammals such as dogs. We propose a method to control a physically simulated iguana character as a representative species of lizards, which can move while physically interacting with the environment, and reproduces the flexible characteristics of a lizard in real time. The main challenges lie in expressing the deformable characteristics of an iguana and adapting low-quality captured motions to various terrain conditions and iguana poses. Our iguana character is designed as a soft-body character, which models the elasticity of an iguana body so that it can express flexible and realistic motions. Applying the motion capture data obtained from an iguana is problematic because it is captured using only a sparse set of markers in an environment different to the simulation environment. To resolve these problems, we transform the low-quality captured motion into full-body motion and adapt it to the terrain in real time using our motion adaptation algorithm. To control the various movements of an iguana, a motion graph is constructed to choose an appropriate motion depending on the situation. The chosen reference motion is adapted to the local terrain, which has irregular height, in real time. A soft-body iguana model is then simulated by physically tracking the time-varying reference motion. We demonstrate that our approach can generate natural and flexible movements of an iguana on hilly terrain.

INDEX TERMS Iguana simulation, soft-body simulation, terrain adaptation, motion graph.

I. INTRODUCTION

Synthesizing realistic movements of characters or objects plays an important role in digital content such as games and films as it can make their audience feel more immersed in the content. For this reason, physics simulation is now widely employed to generate realistic movements of rigid or soft objects in such digital media, such as ragdoll or explosion effects.

To introduce physical realism into the active movements of characters, controllers for physically simulated characters have been intensively studied by researchers. Such studies have mainly focused on the control of bipedal or quadrupedal mammalian characters such as humans or dogs [1]–[11], [11]–[16]. One common feature of these mammalian characters is their relatively high center-of-mass position compared to the supporting area of the feet. This makes maintaining balance one of the most important challenges to overcome.

Other species of animals such as reptiles may exhibit very different types of locomotion. For example, the locomotion of lizards is rather different from mammalian locomotion as they bend their trunks laterally with each step [17], [18]. Thus, it is important to simulate the change in body shape and the resulting forces applied to each body part to reproduce the movement of lizards. Another feature of lizards regarding their locomotion is that they have a relatively low center of mass, which reduces the importance of maintaining balance in the control.

In this study, we propose a control technique to simulate the realistic behavior of an iguana character as a representative species of lizards using a soft-body simulation and motion capture data. We design an iguana character as a soft-body model, which is composed of tetrahedrons and internal springs to simulate the deformable movements of an iguana, such as lateral bending of the trunk. A motion capture dataset is employed to reproduce the natural and realistic behavior of the iguana, but this entails some issues. It is captured using a sparse set of markers and thus cannot accurately represent the actual motion owing to insufficient degrees of freedom. Furthermore, the captured motion data cannot be directly applied to various terrain conditions in a simulation because it is captured in a different environment. To resolve these problems, the low-quality motions captured with a sparse set of markers are transformed into the reference motions of full-body joints in the preprocessing stage and adapted to the terrain in real time using our motion adaptation algorithm. Once the reference motion to be simulated is determined, the desired lengths of the internal springs are calculated to exert internal forces for the soft-body iguana character to track the reference motion.

To select a suitable reference motion for the current situation on the fly, we construct a motion graph based on the transformed full-body motion data. The current reference motion chosen from the motion graph is adapted to the terrain to compensate for the difference between the environment in which the iguana motion is captured and the environment in which the model is simulated. Subsequently, the desired spring lengths are determined based on the terrain-adapted reference motion, and the iguana model can track the motion in an on-line manner using soft-body simulation.

II. RELATED WORK

There have been various studies to simulate soft, deformable objects based on the laws of physics. Baraff and Witkin presented a stable cloth simulation system by taking large timesteps [19]. They coupled existing simulation methods that constrain individual particles with implicit integration methods and improved the numerical stability. The finite element method (FEM) is a widely employed technique for deriving the equation of motion [20]. The robustness of FEM simulation has been improved using inverted tetrahedrons [21], remeshing low-quality distorted meshes [22], or maintaining the volume of an object while changing its shape [23].

Controlling the movement of soft-body objects has been studied to make them move as a user wishes. Tan *et al.* proposed a control system for soft-body characters using the concept of a muscle fiber and FEM without using any skeleton [24]. Coros *et al.* [25] presented a method for controlling the motions of active deformable characters by dynamically adapting rest shapes. Kim and Pollard [26] proposed a fast physically-based simulation system for skeleton-driven deformable body characters. Liu *et al.* [27] presented a simulation and control method for skeleton-driven soft body characters by coupling skeleton and soft body dynamics. Our work is similar to those above, in that it controls a soft-body character. It further extends such work by employing a motion graph to control the locomotion of an iguana.

Controlling biped locomotion in a physically simulated environment has been a long-standing goal of computer graphics and robotics communities. One of the biggest challenges of this problem is to maintain the balance of a character. To address this, many early controllers were designed based on finite state machines and intuitive feedback rules [1], [2]. Some other studies adopted simplified models to abstract the full-body dynamics of humans [3]–[6]. With the motion capture devices being heavily used, motion capture data has been widely utilized to enhance the naturalness of the resulting motions [7], [8]. Optimization techniques have provided powerful tools for improving robustness of controllers or to explore controls for various tasks in a more general formulation of the problem [9]–[11]. Some researchers have studied the control of biped locomotion using musculoskeletal systems [11]–[13]. Most of these studies assume that the simulated model is composed of a set of rigid bodies, and it is actuated by joint torques. Therefore, it is unclear whether these methods can be used to generate the flexible movements of lizards, which include deformation of the body owing to external forces from contact with the ground.

In robotics and computer graphics, researchers have studied the control of simulated quadrupeds. Raibert presented running quadruped robots in his seminal work on robotic running [28], [29]. He also participated in the development of the famous quadruped robot *BigDog* [30]. Coros *et al.* [14] developed a controller for an integrated set of gaits of a quadruped character. Peng *et al.* presented controllers for simulated quadrupeds based on value iteration and deep reinforcement learning [15], [16]. Our method differs from those above in that our iguana character is inherently stable, thanks to its relatively low center of mass and wide support polygon. Thus, no specific balancing algorithm is necessary. Instead, we focus on generating the flexible movements of the iguana using a soft-body simulation.

Using forward dynamics simulators such as ODE [31], DART [32], and SOFA [33] enables the faster development of real-time applications such as games or surgery simulators, based on physics simulation. These have also been employed in many of the aforementioned studies. Among these, SOFA provides a powerful set of features for deformable body simulation. However, we use our own implementation for soft-body simulation, for simplicity. Our aim is to develop a control method for a simulated iguana character, which is different from the goals of these general purpose physics simulators.

III. OVERVIEW

Figure 1 presents an overview of our system. Using captured iguana motion data, we construct a motion graph of iguana motions. At each foot stride, our system selects a suitable reference motion for the current environment by searching the motion graph. The pose of the selected motion is further adapted to the terrain at each frame. After obtaining the adjusted pose for the current frame, an iguana tetrahedral mesh is kinematically mapped to the pose, and the desired length of each spring in an iguana soft-body model is computed. By updating the desired spring lengths at each frame,

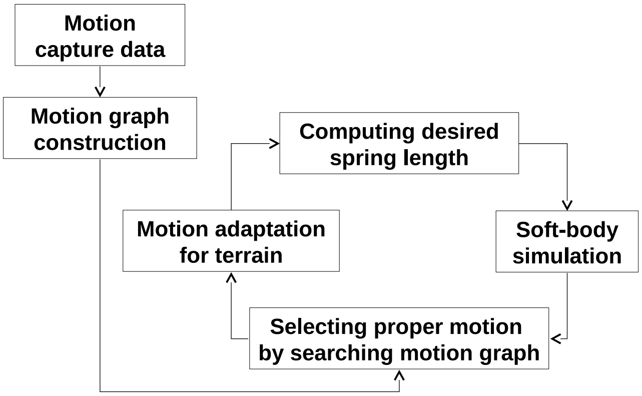

FIGURE 1. System overview.

FIGURE 2. The iguana for our motion capture data is only a few months old, and its length is shorter than 30 cm including the tail. Although there are more than 15 markers attached to the iguana in this photo, only 15 were available in the final motion capture data because it is not easy to keep the markers attached to the small body of the very active iguana. In contrast, more than 40 markers are usually used to capture a human subject.

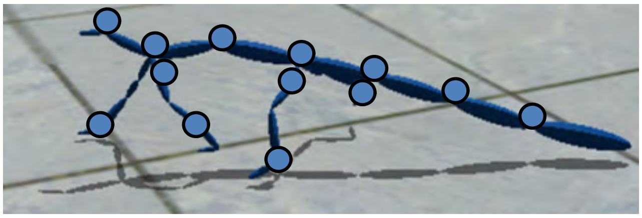

FIGURE 3. Motion capture markers for an iguana. Two markers on the right side of the body are not drawn because they are hidden behind the iguana body.

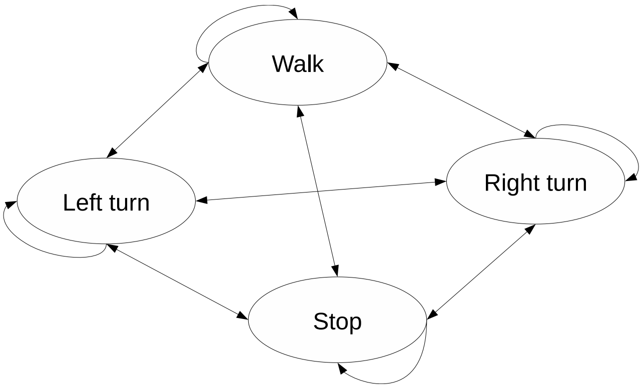

FIGURE 4. The motion graph for our system is composed of nodes connected to each other with bidirectional edges.

our soft-body model is simulated to track the selected reference motion.

IV. MOTION GRAPH CONSTRUCTION

Our iguana motion data has a sparse marker set because it is not easy to keep motion capture markers attached to the small body of a very young iguana (Figure 2). The motion data only has 15 markers: one for each of the four legs, three for the tail, one for the head, and seven for the body (Figure 3). An inverse kinematics solver transforms the motion of the markers into the motion of whole body joints. We construct a motion graph [34], [35] using these transformed full-body motion data.

The nodes of the motion graph are composed of motion clips, each of which is stride-long. The captured motion consists of trotting gait patterns, meaning that the feet touch the ground in diagonal pairs. We segment the captured motions when the contact state changes. Therefore, each motion clip in our motion graph contains a single stride, which is a cyclic motion ending when two feet touch the ground.

Each node connects to each other with a bidirectional edge, and thus the motion graph is designed as a complete graph (Figure 4). Each node contains a short reference motion which is tracked by our soft-body iguana model (Figure 5) in the simulation. The iguana model has a specific state depending on the input of the user, and our system decides whether to keep the current state or change it for each foot step. Because the motion capture data is not sufficiently long and nevertheless there needs to be the motions according to various situations, we elaborately design the complete motion graph by hand.

V. SOFT-BODY IGUANA MODEL

Our soft-body iguana model is designed as a tetrahedral mesh with the modified corotational linear FEM method [36] (Figure 5). It is composed of tetrahedral cells and springs between their nodes. The springs connect every pair of nodes in each single cell and the adjacent cells.

The motion of the iguana model is described by the equation of motion:

$$\mathbf{M}\ddot{\mathbf{p}} = \mathbf{f}_{\mathrm{x}} + \mathbf{f}_{\mathrm{s}} + \mathbf{f}_{\mathrm{e}} + \mathbf{f}_{\mathrm{d}}, \tag{1}$$

where $\mathbf{M}$ represents the mass matrix of the discretized soft body, and $\mathbf{p}$ represents the node position in a deformed shape. Here, $\mathbf{f}_{\mathrm{x}}$, $\mathbf{f}_{\mathrm{s}}$, $\mathbf{f}_{\mathrm{e}}$, and $\mathbf{f}_{\mathrm{d}}$ represent the external force, spring force, elastic force, and damping force, respectively.

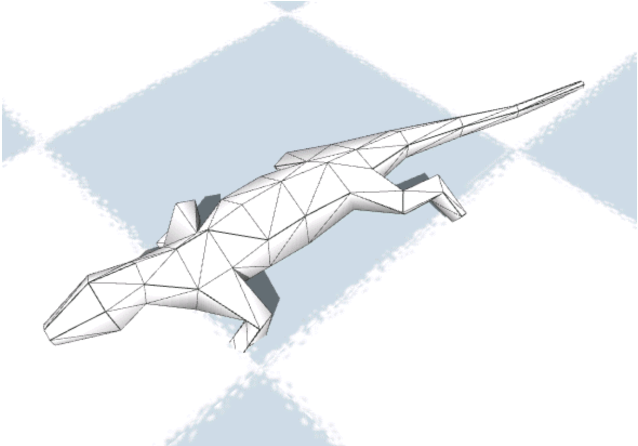

FIGURE 5. Our soft-body iguana model is designed as a tetrahedral mesh.

The external force $\mathbf{f}_\mathrm{x}$ consists of the gravitational force and ground reaction force, which are essential components to describe physically correct movements of the iguana model.

The spring force $\mathbf{f}_\mathrm{s}$ drives the active movement of the iguana model. Our iguana model is actuated only by this internal force, and moved by the resultant ground reaction force and the gravity force. Each spring attempts to return to its desired length. We can express the force generated by the springs as follows:

$$\mathbf{f}_\mathrm{s} = \mathbf{a}(\mathbf{l}_\mathrm{d} - \mathbf{l}), \tag{2}$$

where $\mathbf{l}_\mathrm{d}$ and $\mathbf{l}$ represent vectors containing all the desired and current spring lengths in the model, respectively, and $\mathbf{a}$ is a scaling constant that determines the magnitude of the spring force.

To apply an elastic force to each node, we employ the following formula proposed by Nesme *et al.* [37]:

$$\mathbf{f}_\mathrm{e} = -\mathbf{B}^T\mathbf{D}\mathbf{B}(\mathbf{p} - \mathbf{R}_\mathbf{x}), \tag{3}$$

where $\mathbf{x}$ represents the node position in the material rest shape, $\mathbf{R}$ is used to transform from the reference coordinate to the deformed coordinate, and $\mathbf{B}$ and $\mathbf{D}$ represent the strain-displacement matrix and the stress-strain matrix in the deformed coordinate, respectively. This elastic force term makes the simulation more robust because it helps to avoid degenerate cases, which can occur when the tetrahedrons deform too much.

As a damping force, a Rayleigh damping model was employed as follows:

$$\mathbf{f}_\mathrm{d} = -\mathbf{C} \cdot \dot{\mathbf{p}}, \tag{4}$$

where $\mathbf{C}$ is the damping matrix [24].

At each frame, the desired spring length $\mathbf{l}_\mathrm{d}$ is calculated to track the terrain-adapted version of current reference pose chosen from the motion graph, as described in Sections VI and VII. All the computed forces are numerically integrated to simulate the motion of the iguana model. To prevent large deformations of the iguana leg length, relatively high stiffness springs are employed. An implicit integration method is employed for the numerical stability of the integration of the equation of motion. The ground reaction force is calculated using a penalty method.

VI. MOTION ADAPTATION FOR TERRAIN

All motions in the motion graph are suitable for the environment in which they are captured, which is a plane. To simulate the iguana model in various environment, the motions need to be adapted to the terrain on which the iguana model is moving. This process comprises two steps: *plane fitting* and *residual fitting*, which adjust the position and orientation of the whole body and the positions of the feet and tail in the current reference pose to be tracked.

From each adapted reference pose at each frame, we obtain the desired spring length as described in Section VII. Then the simulation is integrated with the forces that are calculated as described in Section V.

A. PLANE FITTING

This step aims to match the heights of the feet from the terrain in the simulation environment as closely as possible with those in the motion capture environment, by rotating and translating the iguana model.

First, the height of each foot from the ground in the original reference pose selected through the motion graph search is defined as the *residual height* (Figure 6, top). Then the position of the foot is projected onto the surface of the terrain. Each target foot position can be computed by adding the *residual height* to the projected foot position (Figure 6, middle). Next, we calculate the rigid transformation that minimizes the error between the target feet positions and those of the current reference pose. This transformation is applied to the current reference pose to avoid any part of the reference pose from penetrating the ground and the distance between the feet becoming too large or small (Figure 6, bottom). The rigid transformation matrix can be simply obtained using Singular Value Decomposition (SVD) because the correspondences between the feet are already known.

B. RESIDUAL FITTING

There are still errors between the target feet positions and the feet positions fitted by the *plane fitting* because only a rigid transformation is applied. Thus some of the feet and tail might still penetrate the terrain after applying the *plane fitting* (Figure 7, top). Even if the terrain is just a tilted plane, the feet positions fitted by the *plane fitting* and the target feet positions cannot be the same because the distance between any two target feet positions and that between the corresponding pair of feet positions in the original reference pose are different.

The tail height also needs to be adapted to the ground, because the tail is not considered in the *plane fitting*. The target tail positions are computed in a similar manner to the target feet positions in the *plane fitting*, by adding the

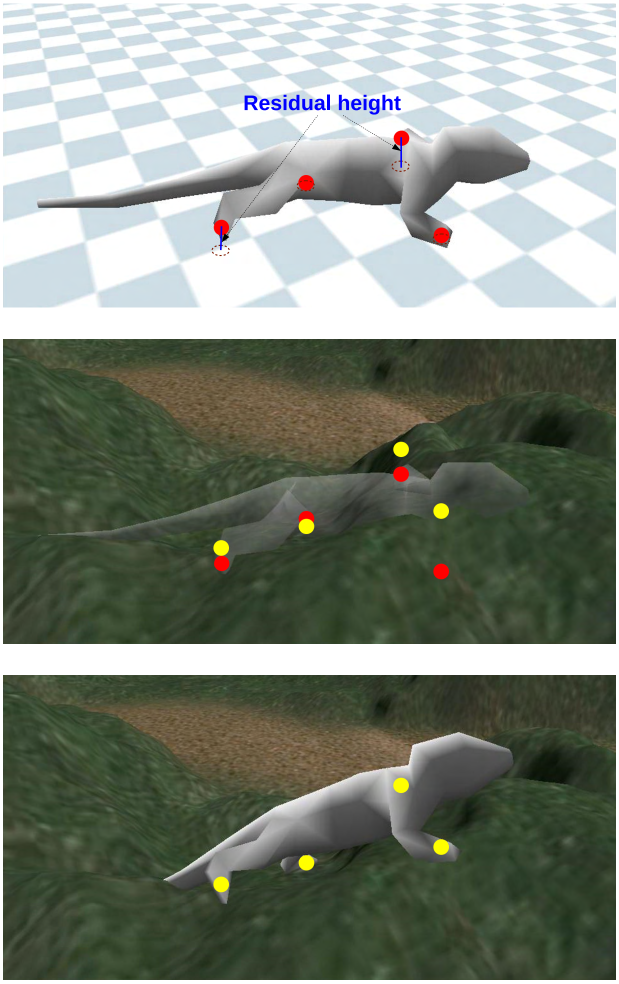

FIGURE 6. ***Plane fitting*. Top: An original reference pose on the ground plane. The red circles indicate the positions of the feet. The blue line segments indicate the *residual heights*. Middle: The original reference pose is rendered on the terrain. The red circles show the original feet positions and the yellow circles indicate the target feet positions, which represent the sum of the projected feet positions on the terrain and the corresponding *residual heights*. Bottom: Through the *plane fitting* step, the best rigid transformation to match the original feet positions to the target feet positions is computed and applied to the iguana model. Note that the *plane fitting* is performed on the skeletal reference pose, but we visualize the modified pose with a skinned *reference mesh* (described in Section VII) in this figure.**

residual height of the tail to the projected tail position on the terrain.

To remove these remaining errors for the feet and tail, we further adjust their positions to the corresponding target positions reflecting the ground height by using an inverse kinematics solver (Figure 7, bottom). We employ a fullbody IK solver based on nonlinear optimization which uses the L-BFGS method for both the *residual fitting* and the motion graph construction (Section IV).

VII. SPRING LENGTH COMPUTATION

To compute the desired spring length, we use a *reference mesh* that is identical to the tetrahedral mesh of the soft-body iguana model (Figure 5). The vertices of the *reference mesh* are kinematically mapped to the current pose of the

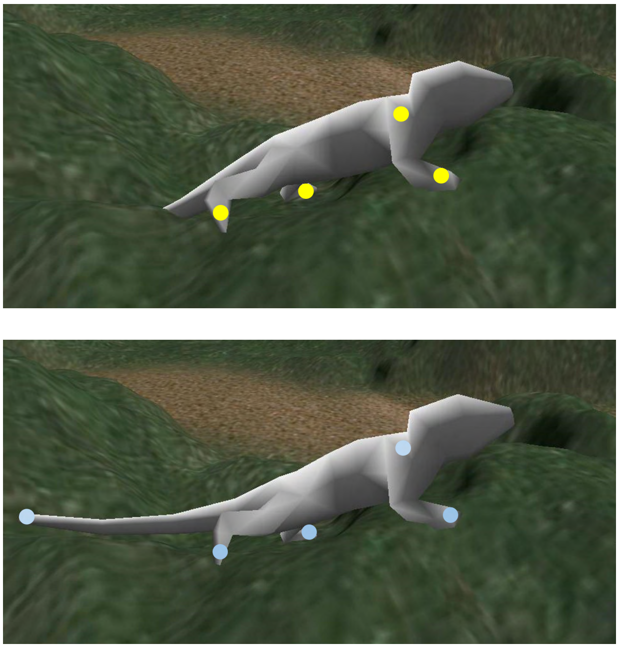

FIGURE 7. ***Residual fitting*. Top: Before the *residual fitting* is applied, there are some deviations from the target feet positions (yellow circles) and the real positions of the feet, and penetration of the tail. Bottom: After the *residual fitting* is applied, the positions of the feet and tail closely match their target positions (skyblue circles).**

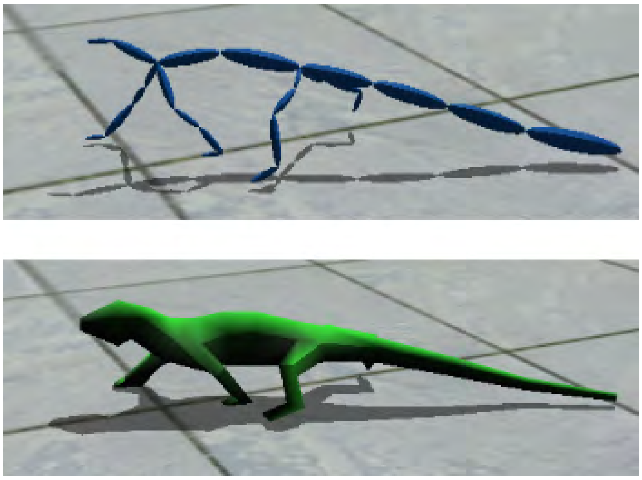

FIGURE 8. **The *reference mesh* of our iguana model. Top: A single pose in the full-body skeletal motion of the iguana. Bottom: The *reference mesh* skinned to that pose.**

terrain-adapted motion using the dual quaternion skinning method [38] (Figure 8). Subsequently, the desired spring length ($\mathbf{l}_d$ in Equation 2) between the nodes in the iguana model are updated to the distances between the corresponding vertices in the *reference mesh*. This generates internal spring forces for the soft-body model to track the deformation of the *reference mesh*.

This kinematic mapping is only used to calculate the desired spring length, and the skeleton information is no longer used in the actual soft-body simulation process.

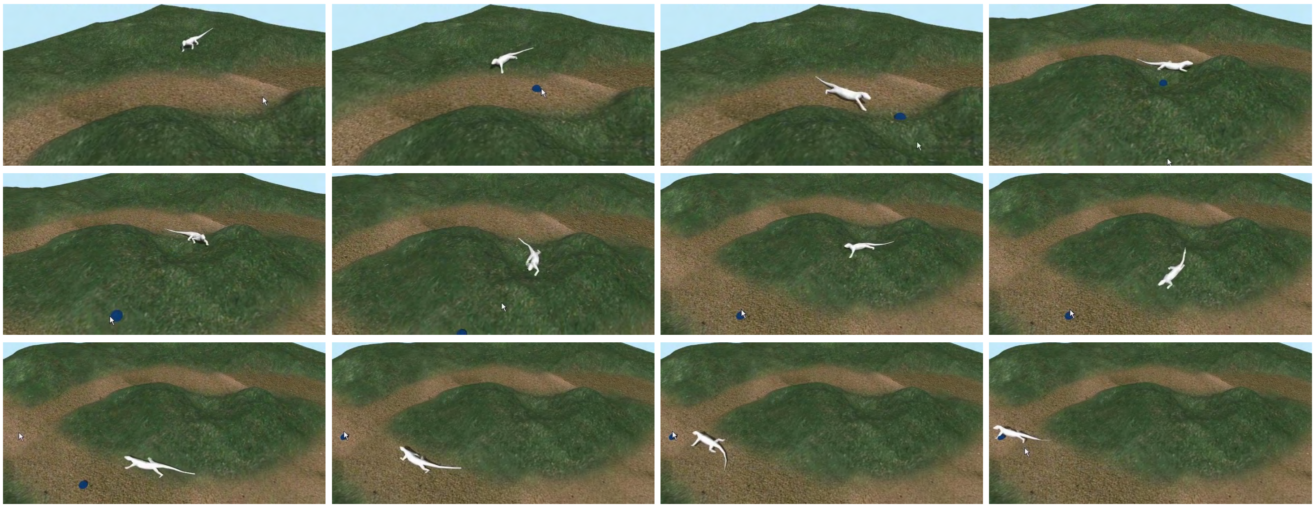

FIGURE 9. Simulation of the iguana model walking to the target position (blue sphere) pointed by a user (ordered in left to right and top to bottom).

We synchronize the current position and orientation of an iguana in the motion graph with those of the simulated iguana so that the errors are not accumulated.

VIII. RESULTS

We use our implementation for building the equations of motion and their implicit integration. The time-step of the integration is 1/1200 seconds. The iguana motion is captured at 30 Hz, and thus the reference motion pose is updated every 1/30 seconds in a real-time simulation. This update includes the motion adaptation for the terrain and the desired spring length computation. The simulation runs approximately two times faster than real-time on an Intel i5 machine. The mass and length of our iguana model are 4 kg and 85 cm, respectively, and the gravitational acceleration and friction coefficient are set to 9.8m/s^2, respectively, and 1.0 in our experiments. Although the iguana for our motion capture is only a few months old, we use the weight and length data of adult iguanas between four and five years old, for generality [39].

A. INTERACTIVE LOCOMOTION CONTROL OVER UNEVEN TERRAIN

In this experiment, a user points a target position of the iguana model on uneven terrain (Figure 9). Then the iguana model decides its states depending on the situation and exhibits an appropriate movement to the target position using a soft-body simulation. The simulated iguana was able to successfully walk over irregular ground with natural motion owing to the utilization of motion capture data. The natural deformation of the iguana body is effectively expressed by a soft-body simulation, which cannot be achieved by a rigid body simulation. Our soft-body simulation system is also able to generate physically realistic interaction with environments, such as ''slipping'' motions as shown in the accompanying video. This cannot easily be achieved by a kinematic approach using only inverse kinematics and skinning.

B. MOTION ADAPTATION FOR A SINGLE POSE

To visualize the result of the motion adaptation step (Section VI), we applied the motion adaptation algorithm to a single pose in the iguana motion data and visualized it as a skinned *reference mesh* (Figure 10). Moving the pose around on uneven terrain, the algorithm adjusted it to the terrain on which it was located. This allows our simulated character to exhibit a wide range of terrain-adaptive actions using only a small set of captured motion.

C. EFFECT OF MOTION ADAPTATION

We compared the results of the iguana walking over irregular ground with and without the motion adaptation to terrain (Figure 11). With the motion adaptation, the iguana model could easily move over the hill in the initial forward direction without slipping. The height differences between the feet, tail, and hilly terrain in the simulation environment remain as close as possible to the corresponding height differences in the motion capture environment in this case, which means that the stumbling or slipping of the feet is significantly reduced. Without the motion adaptation, the iguana model easily becomes stuck in a small groove and cannot maintain its original target direction. In this case, the stance feet, swing feet, and the state of whether the tail touches the ground might be different for the current state of the simulated model and the corresponding reference pose on a plane because the height differences are not adjusted. This causes the feet of the simulated model to frequently slip or stumble. We found that adapted feet and tail positions in the reference motion played important roles in locomotion stability on the irregular ground.

D. EXTERNAL PUSHES

One of the benefits of using physics simulation is that the generated movements are always physically accurate even if there are unexpected disturbances such as external pushes. To demonstrate this aspect, we conducted push experiments

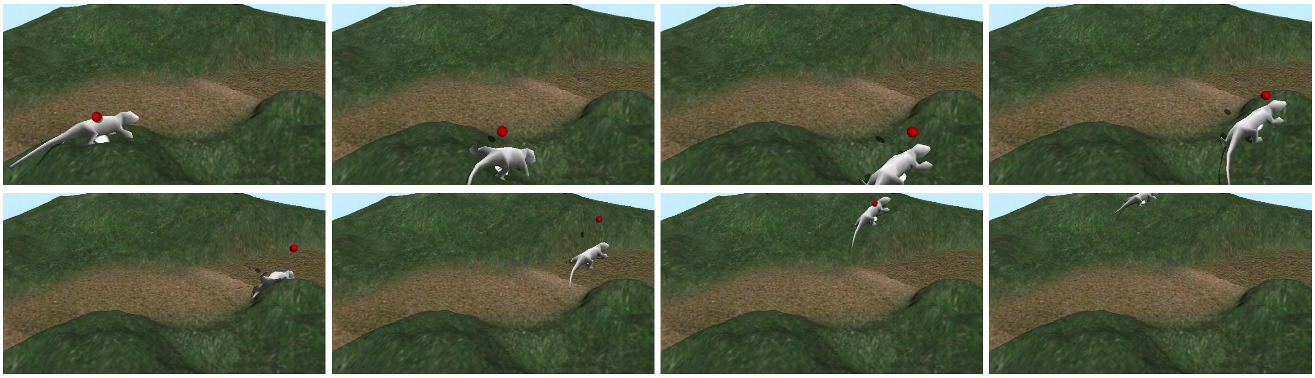

FIGURE 10. A terrain-adapted *reference mesh* of the iguana model. A user moves the *reference mesh* and it is smoothly adapted to the curves on the terrain (ordered in left to right and top to bottom).

FIGURE 11. Comparison of the simulation with (top) and without (bottom) using our motion adaptation algorithm. Top: With the motion adaptation, our iguana model easily moves right over the hill following its forward direction. Bottom: Without the motion adaptation, the iguana model is stuck in a small groove and cannot move in its target direction.

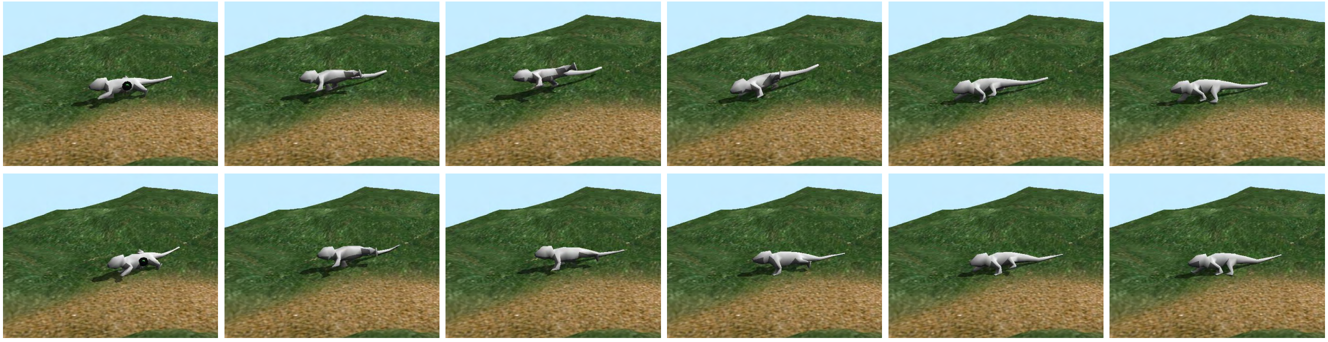

FIGURE 12. An external force is applied to the iguana models with moderate stiffness (*normal model*, top) and with softer springs (*softer model*, bottom). Each green arrow in the leftmost images (which looks like a black circle because we're looking at its back) indicates the external force. Note that the *softer model* is pushed less than the *normal model* for the same duration and magnitude of external force. The time interval between each column is 0.2 seconds. .

with two types of iguana models (Figure 12). The first uses springs with moderate stiffness, the same as those used in other experiments (*normal model*), and the other model uses "softer" springs (*softer model*). In the experiments, we applied forces of 40 N for a duration of 0.1 seconds to the left side of these models' trunks while they were walking. When external forces of same duration and magnitude were applied, the *softer model* was pushed less than the *normal model*. This is because the soft springs of the *softer model* better absorb the impact from the outside. Both models were usually pushed by external forces to some extent and then returned to their original step without any balancing mechanism, owing to their low center of mass position, unlike in previous studies controlling biped or quadruped characters [11]–[16]. Thus, our iguana model might lose its balance in some exceptional cases. For example, the second push to the *normal model* in the accompanying video. Another interesting observation is that the feet of the *normal model* more frequently slide than those of the *softer model*. This is probably because the stiffer feet of the *normal model* only allow a smaller contact area than those of the *softer model*. Therefore, this results in more foot rotation and sliding.

IX. DISCUSSION

We propose a system to control a soft-body model of a lizard species, namely the iguana. The movement of an iguana is highly flexible, especially in terms of its lateral trunk bending while walking. Thus, it is reasonably effective to employ a soft-body simulation technique to express the movement. We construct our system using a soft-body simulation, motion graph technique, and novel motion adaptation algorithm based on inverse kinematics. This combination of techniques allows us to interactively control the simulated flexible movement of a soft-body iguana model over uneven terrain.

Our system is able to simulate the movement of the iguana model faster than real time, even though it employs a soft-body simulation. Using a small number of vertices of the soft-body model and omitting skeletal information during simulation enables this fast simulation. The model without a skeleton might result in varying inter-articular distances. However, as shown in the accompanying video, the changes in distance are not noticeable, owing to the use of high-tension springs.

In the accompanying video, the feet of the iguana model sometimes slide on the terrain. We determine that this foot sliding can occur for multiple different reasons, such as the foot springs being too stiff, insufficient friction coefficients, and contacts from other body parts such as the trunk or tail. As shown in the accompanying video, the iguana model slides more frequently when the reference motion is not adapted (and therefore there are many unintended contacts between the body parts and the terrain) or the value of the spring stiffness is set above a suitable level. Additional careful tuning of the friction coefficient and spring stiffness would result in a more stable locomotion simulation.

Lateral bending of the trunks of lizards prevents significant respiration, which is known as *Carrier's constraint* [40]. It is very difficult for lizards to concurrently move and breathe, because lateral bending of the body expands one lung and compresses the other, so that the total volume of the lung does not meaningfully vary. This is why lizards repeatedly take rests after short moves. Modeling their respiratory system and simulating this using our soft-body model would be an interesting future research topic.

Despite the fact that many digital contents, such as games or films, have been produced with main characters consisting of the quadrupedal animals or hexapod insects, studies on controlling physically simulated characters have so far focused mainly on bipedal humanoid models, and therefore balancing control has been the main concern. In recent years, studies on controlling quadrupedal characters that have also focused on balancing have been published [14]–[16]. Our work presents another method of controlling quadrupeds, focusing on another aspect of a particular species of quadrupedal animals: the flexible bodies of lizards. Extending our system to handle a wider range of motions, such as running or attacking, would be a good direction to increase the practical usability of our system. Controlling other species of reptiles with flexible bodies, such as snakes, would also be an interesting future research topic.

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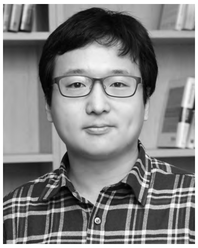

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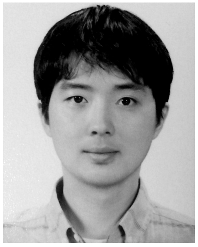

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