Self-Driven Soft-Body Creatures

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***Abstract*—Virtual characters play an important role in computer-generated environments, such as, video games, training simulations, and animated films. Traditional character animation control methods evolve around key-frame systems and rigid skeletons. In this paper, we investigate the creation and control of soft-body creatures. We develop creatures that learn their own motor controls and mimic animal behaviours to produce autonomous and coordinated actions. Building upon passive physics-based methods and data-driven approaches, we identify solutions for controlling selective mesh components in a coherent manner to achieve self-driven animations that possess plausible life-like characteristics. *Active soft-body animations* open the door to a whole new area of research and possibilities, such as, morphable topologies, with the ability to adapt and overcome a variety of problems and situations to accomplish specified goals. We focus on two and three-dimensional deformable creatures that use physics-based principles to achieve *unconstrained self-driven motion* as in the real-world. As we discuss, control principles from passive soft-body systems, such as, clothes and finite element methods, form the foundation for more esoteric solutions. This includes, controlling shape changes and locomotion, as movement is generated by internally changing forces causing deformations and motion. We also address computational limitations, since theoretical solutions using heuristic models that train learning algorithms can have issues generating plausible motions, not to mention long search times for even the simplest models due to the massively complex search spaces.**

Keywords–animation, control, soft-bodies, characters, motion, physics, deformation, creatures, movement, unconstrained, physics-based, self-driven

I. Introduction

Movement without a Skeleton Soft-body creatures are organisms or animals that lack a skeleton (a real-world soft-body example, would be a leech, a jellyfish, or a even a tongue). The question of how to efficiently represent the creature and create 'controlled' movement is an open topic of research. As soft-body creatures do not have the luxury of an internal **musculo-skeleton** system to guide and steer their motion, but must instead generate movement solely on the contraction and expansion of their body tissues. Another key thing to remember, is soft-body creatures are not confined to anatomically-based structures (such as, bipeds or quadrupeds) and provide a means of freedom and creativity. The creation and controlling of self-driven soft-body creatures with scalable properties that learn their own motor controls and mimic animal behaviors to produce autonomous and coordinated actions is an important and challenging subject.

Control & Realism Skeleton key-frame methods are the dominant solution for creating controlled creature animations. As they offer an intuitive, flexible and powerful solution that can produce highly realistic results. However, can skeleton based models generate animations that move and look the same as a soft-body system? Assuming a soft-body creature must keep its overall volume, a soft-body system is able to squeeze and reduces its circumference and stretch to increases its length. The internal deformations generate movement and provide a visible set of secondary visual characteristics that add a natural aura to the motion that are not apparent in purely rigid simulation solutions.

Contribution This paper presents a soft-body creature control system with scalable properties (i.e., trade-offs between computational speed and detail). Our approach makes the following technical contributions: (1) generation of steerable deformations that control a character's soft-body motions to achieve targeted animations under their own forces (unconstrained movements through internal forces and contacts with the environment); (2) the model does not require any intensive off-line pre-processing, enabling artists to re-iterate multiple versions quickly and efficiently to develop more creative and imaginative solutions (enabling artistic freedom); and (3) we create controlled animations that interact with the physical simulation (e.g., push disturbances and secondary motions, such as, vibrations and ripples).

Road Map The rest of the paper is structured as follows: First, Section II discusses related work. In Section III, we give a explanation of our algorithm and practical considerations for real-time environments. Section IV presents the results from the simulation examples. Section V discusses the implication of the method and explains any problems after taking the results into consideration. Finally, Section VI draws conclusions from the approach and future work.

II. Related Work

There has been lots of work into 'passive' soft-body systems, such as, skin and cloth [1], [2]. These techniques provide a wealth of information that we build upon in this paper to construct animated soft-body creatures. The recent work by Cheney et al. [3] and Kenwright [4] inspired the research behind in this paper. Presenting innovative solutions that go beyond traditional key-frame based methods towards more esoteric procedural ones. For example, this includes, a muscle-driven solution by Tan et al. [5] who creates animated soft-bodies using an action line and helical muscle fibers for twisting movements. Combined with key-frame data prescribed by an animator to steer and direct the resulting simulations and generate life-like deformations (i.e., primary motions for movement and secondary motions for appeal).

The area of soft-body creatures covers a diverse range of topics across multiple disciplines. For instance, soft-body creatures does not mean just 'land' creatures, but can also be controlled muscle segments, like the tongue, not to mention flying and swimming animals. A good example of this, is the work by Tan et al. [6] who did ground breaking work into soft-body fish simulations. The research in soft-body creatures also

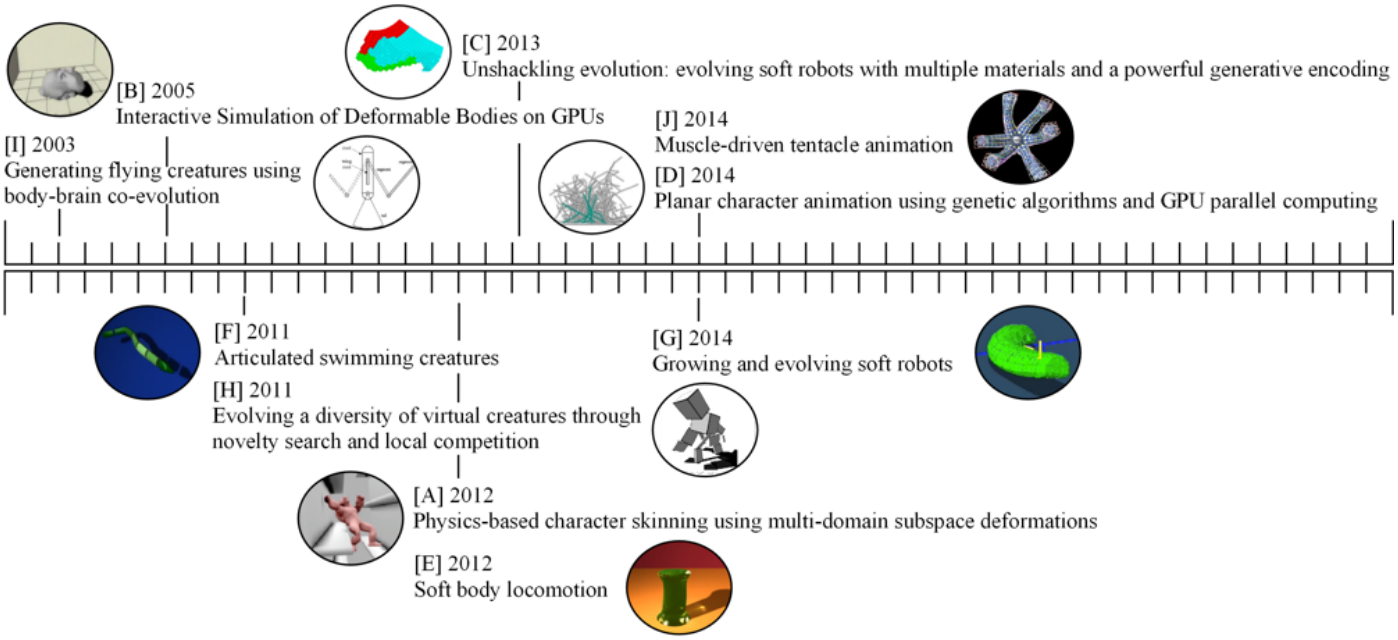

Figure 1. **Timeline** - Visual illustration of related publications over the past few years that have contributed towards more active and engaging soft-body systems. [A] [1], [B] [2], [C] [3], [D] [4], [E] [5], [F] [6], [G] [7], [H] [8], [I] [9], [J] [10]

spins out to real-world models, such as, robots that grow and evolve [7]. The paper 'Unshackling Evolution: Evolving Soft Robots with Multiple Materials and a Powerful Generative Encoding' by Cheney et al. [3] used a technique that divided the object into 'components' (i.e., voxels) to create the controlled motion. Then there was Lehman and Stanley [8], who evolved a diverse range of creatures through a novelty search and local competition. Shim and Kim [9] created flying creatures using body brain co-evolution, while Liu et al. [11] focused on a hybrid skeleton to control the soft-bodies. A number of these soft-body techniques have employed the 'action-line' control system in combination with an optimisation search to steer and direct the animation [5], [12]. For instance, a muscle-driven tentacle animation by Stavness [10] and the soft-body locomotion by Tan et al. [5]. In conclusion, active self-driven soft-body creatures offer a novel solution for solving a wide range of potential problems (see Figure 1 for a brief visual illustration of inspiring research on the topic over the past few years).

Our work: Our work focuses on the ability to create imaginary and non-imaginary topologies and have them move in a controlled manner (e.g., hop or walk along) driven under their own internally changing forces. We incorporate techniques from passive physics-based simulation systems and coarse control meshes to reduce computational costs. While we use an underpinning physics-based model, we integrate in control approximations, such as, coordinated rhythmic oscillations, to control and direct the soft-body's movement towards an organic and aesthetically pleasing solution.

III. Method

A purely procedural soft-body solution is plausible using heuristic algorithms. For example, training trigonometric functions (e.g., any signal can be composed of sinusoidal signals - the concept behind Fourier series [13]). However, this opens the door to a vast array of parameters with a finite search range that is difficult to solve in viable time frames and allow for artistic control. Alternatively, we exploit a smarter solution uses a hybrid combination of methods, such as, pre-recorded training data to steer the system towards approximate solutions, in combination with human intervention to create self-driven soft-body actions. We take animation data (i.e., pre-recorded key-frames). We connect the soft-body to the skeleton via distance constraints, so as the animation plays the points will move in a correlated pattern. As an important factor is the creation of soft-body motions that are controllable (rather than just randomly jiggling around). The kinematic solution of the coupled system provides a starting set of oscillating distance constraints from which we can calculate the penalty forces and inverse dynamics. When we play back the soft-body system using the calculated forces. The motions will be driven by the physical system, and will only be approximate, but will capture a starting essence for the animation (based on the key-frame data). Of course, the motion will drift away from the pre-defined target set out by the key-frame data (the animation will fall over or wobble to one side). This is where we need to adapt and adjust the forces to steer and control the final animation. Allowing an animator to use key-frame motion initially to target and formulate the underlining motion for the soft-body and aid in the rapid proto-typing and development (see Figure 2). Since the final simulation is generated using physics-based concepts, the deformations are organic with directable purpose (i.e., walk or move in a desired way - artistic influence).

Our physically-based approach to soft-body animation evolves around the automatic control of the contractions/expansions of interconnected constraints. The internal forces drive the soft-body model's motion. The formulation

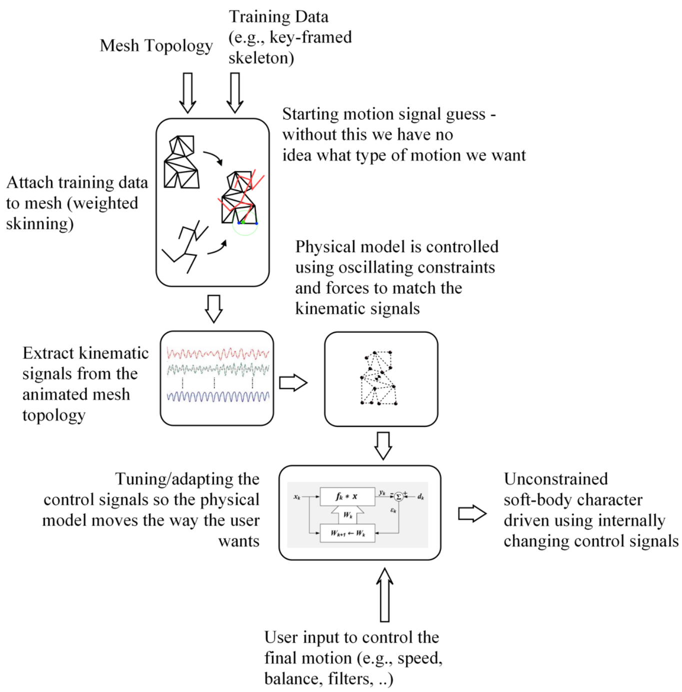

Figure 2. **Overview** - Interconnected elements to construct and tune our soft-body character's unconstrained motions.

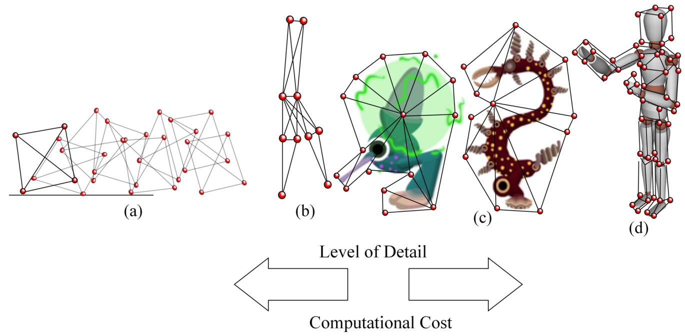

Figure 3. **Animating Soft-Body System** - Decomposing the model into elements (e.g., point-masses) and controlling the interconnected elements to achieve directed animations.

of a passive soft-body system is straightforward, with the challenges evolving around the control of the internal forces to achieve directed motion. Penalty-based methods and inverse dynamic calculations allow us to solve for desired forces to accomplish positional changes. **Combining animator controlled targets** with a dynamic force driven simulation, we capture the global movement specifications of the animator (artistic characteristics) and achieve detailed body deformation effects that appears organic and life-like (i.e., analogues to a real-world organic creature). We emulate a secondary underlying deformation motions that include squeezing and bulging through lengthening, bending, and twisting movements in a free moving action **without an internal skeleton**. We use a point-mass structure with a spring-damper system for experiments that do not require exact solutions (i.e., quick proto-typing/investigation). For more precise solutions (i.e., conservation of momentum and stiff-constraints), we use a finite element composition and a constraint based solver. Decomposing the mesh into a finite-element structure (triangles in 2D and tetrahedrons in 3D). Oscillating the rest forces between the constraints to create rhythmic movements.

A. *Motion Mechanics*

We explore and propose two methods for generating soft-body motions, i.e., procedural (trigonometric) and data-driven (signal-data).

Trigonometric (Fourier Series) For some systems, a goal is specified, such as, walking speed or jumping height. For a highly coupled system, it can be difficult to achieve a unified motion to accomplish such an action. Applying the concept that any signal can be represented by a series of sinusoidal signals. We use an optimisation algorithm to train the trigonometric parameters (i.e., amplitude, frequency and offset) to achieve a motion which accomplishes a specified fitness criteria. The output from the trigonometric solution may also form a good approximation for artists to start from. The signals from the trigonometric functions can be saved and modified to create more aesthetic solutions.

Trained/Customized Signals The ability to allow an artist to customize and adapt constraint signals is important for freedom of creativity. For example, it is difficult to train soft-body motion signals using purely key-frame data, as animations, such as, jumping - require the body to squash and conserve energy then release it to achieve a jumping motions. Additionally, if a signal is created by an artist, we are able to use Fourier transform to extract parameters or even filter components to target different motions.

B. *Overall Volume & Shape*

A point-mass system offers a simple and intuitive solution for the majority of cases. However, there are situations that require the shape to be distorted, while preserving the overall volume. For these situations, a finite element method (FEM) is required (i.e., area and Young's modulus calculation). FEM keeps track of the internal volume by distribution of pressure forces outwards via the connecting corner points (i.e., assuming a triangle or tetrahedron configuration).

For a point-mass system with distance constraints, we limit contraction/expansion, (e.g., 10% to keep the overall appearance and some form of the original shape) in addition to limiting forces, while for volume regulation using an FEM topology, each partitioned segment must retain its original volume, within some tolerance, allowing the shape to deform and stretch (for instance, taking a small fat object and stretching it into a thin long one, analogues to a leech contracting and stretching but continuing to hold the same volume).

C. *Low-Resolution Control Mesh*

We explain our low-dimensional control model for creating controlled deformations and ultimately the goal of self-driven soft-body creature animations. A coarse control mesh technique is used to reduce the computational overhead and the mathematical complexity of the model, so we are able to achieve real-time frame rates and quick turn-around times. We explain how the high-resolution graphical mesh interactions with the coarser control mesh and how contacts between the mesh and the virtual environment are handles (i.e., in an endeavour to realistically mimic the mechanical deformation properties of organic tissue).

Mesh embedding, which is also called *free-form* deformation [14], [15], uses a low-dimensional coarse volumetric mesh to enclose the entire deformable body in order to represent the behavior of the body. The location of every material point inside the deformable body is determined by interpolating the positions of the neighboring nodes in the mesh. Since the work by Faloutsos et al. [16], mesh embedding techniques have been widely used to simulate soft-bodies in the graphics literature [17]–[19]. We chose mesh embedding to reduce complexity of the deformable body in our simulation system not only because the technique can reduce the model complexity without losing the fine geometry of the object but also because the frame can be manipulated more easily and efficiently using the embedding mesh system compared to modal reduction. In our formulation, the control body is the core soft-body system that drives the deformations and ultimately the animation. The complete system consists of a set of deformable body elements (i.e., tetrahedrons or voxels) and a physics-based soft-body core (see Figure 4).

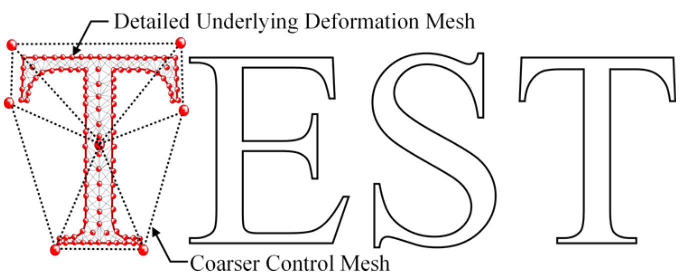

Figure 4. **Coarse Control Mesh** - Reduce the complexity of the problem while preserving the underlying soft-body's freedom.

The position of a material point in the deformable body is determined from the nodal positions of the coarse mesh through interpolation. Initially, we automatically assigned weights and blended the vertices based on the inverse distance between the coarse mesh control nodes and fine mesh vertices (i.e., distance-based falloff weighting). However, since the mesh is partitioned into regions (cells), triangles in 2D and tetrahedrons in 3D, it is possible to assign vertices into region. For example, every point inside a tetrahedron can be expressed as a linear combination of the four control vertices. For every vertex p in the high-resolution mesh, we look up the tetrahedron that the point is in, which has four control vertices (call them v_0, v_1, v_2, v_3). If we translate every vector by $-v0$, we can write the new point $p' = p - v_0$ as a linear combination of v_1', v_2', and v_3'. This gives us a new equation for p', namely $p' = u\ v_1' + v\ v_2' + w\ v_3'$, where u, v and w are the weights (i.e., Barycentric coordinates). Now we can write the point p as $v_0 + u(v_1 - v_0) + v(v_2 - v_0) + w(v_3 - v_0)$. Deforming the tetrahedron mesh, v_0, v_1, v_2 and v_3 will change p accordingly. This deformation will depend on the four nearby vertices, and thus a deformation on one side of the mesh will have no effect on the other side of the high-resolution mesh (unlike the distance-based falloff, where every vertex affects every other vertex in the high-resolution mesh - see Kenwright [14] for further information).

Level of Detail (LOD) Adjusting the complexity of the problem by subdividing the mesh into a coarser 'control' sub-

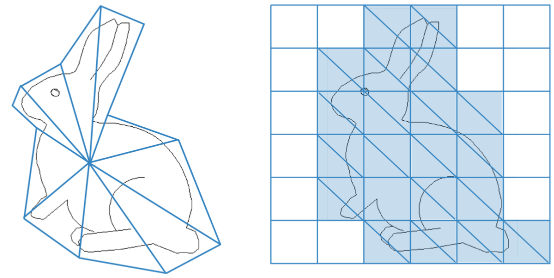

Figure 5. **Elements** - Variety of coarse mesh configurations, the two main ones we focused on, were tetrahedrons (left) and voxels (right) (e.g., Figure 8 shows the voxelated gummy-bear mesh).

meshes allows us to scale the complexity of the problem. This analogy is similar to the work by Kim and Pollard [15], who focused on fast and efficient skeleton-driven deformable body characters, however, our model uses the underlying deformation to achieve the controlled creature motions (Figure 3).

Scalability We endeavour to automate the modelling/creation process as much as possible, and reduce the amount of artist workload by providing a system that enables both productivity and creativity. A low-poly control mesh enables artists to easily proto-type key-frame motions quickly and easily in real-time (see Figure 4 and Figure 5). Proving an artistic tool for investigating deformation effects and adjusting them to different platforms (i.e., reducing the model complexity to more coarser representations for environments with limited resources, such as, memory and processing power).

IV. Experimental Results

Experimenting with a low-dimensional 2D model initially provides the basis for more complex systems. Adjusting the mesh/point-mass/constraint details in 2D and 3D, combined with oscillatory rhythmic input from trigonometric sources and pre-trained signals from either an artist or from motion capture data. This includes, simple hopping and wiggling locomotion for cubes to more complex structured motions with a larger interconnected set of constraints. Simulations:

- simple 2-dimensional square bouncing along ground (i.e., forward and backward) - the motion is generated by contracting and expanding the edges of the square in a controlled unified manner (see Figure 6)
- more complex 2-dimensional shapes (e.g., convex and concave)
- 3-dimensional shapes (i.e., cubes and tetrahedrons) (see Figure 7)
- coarser models (i.e., lower dimensional control shapes creating the motion combined with a higher resolution mesh) (see Figure 8 and Figure 9)

Preliminary experiments evolved around 'rhythmic' algorithms using trigonometric functions (i.e., Fourier series). Truncating series of sinusoidal signals with different parameters for the different constraints, makes it is easy to construct simple gait motions (i.e., low-dimensional models like cubes and pyramids). Crucial factors are 'friction' and 'constraint fighting'. Not only is friction important to prevent the model simply skate on the spot, but also the ‘unified’ cooperation of the different signals. Manually adjusting parameters to achieve controlled action are possible for simple models, but difficult for more complex systems. The simulations demonstrate the character’s ability to adapt and learn their own motor controls to mimic animal behaviours and create autonomous and coordinated actions. Finally, since we are training a coarser low-dimensional control mesh, it helps address computational bottlenecks.

Limitations A system of interconnected nodes representing the soft-body mechanism can grow in complexity quickly and make it difficult to formulate and train a controlled solution to accomplish directed actions. An interesting area of future exploration is that of massively parallel architecture to divide the workload of the problem across a large number of smaller cores (e.g., the graphical processing unit (GPU)). Coupled with the question of ‘comfort’ and ‘shape’, since we may want our creatures to move in an organic and relaxed manner while keeping their overall form. Of course, this may not be the case - since the approach allows the ability to change shape, possibly to overcome environmental situations or accomplish some artistic desire, which is important and challenging.

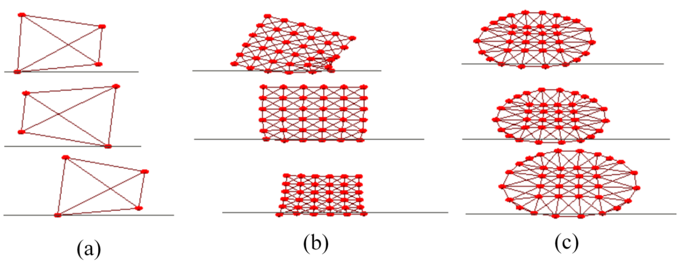

Figure 6. **Screenshot** - (a) A 4-point mass-spring topology using coordinated oscillating constraints to create a rhythmic gait like motion as seen by quadrupeds. (b) Increasing the mass distribution enables more complex deformations and motions but introduces additional difficulties creating ‘coordinated’ movement (i.e., avoiding constraint fighting). (c) Experimenting with shapes, like circles, we can create stepping motions analogous to the box-quadruped system, or rolling like motion as seen by a vehicle tyre.

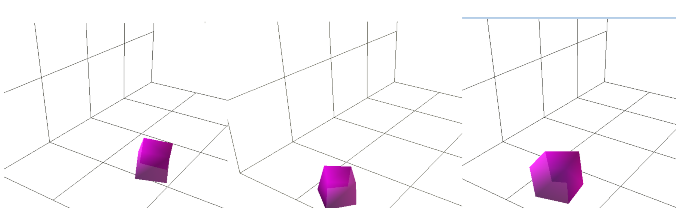

Figure 7. **Screenshot** - For low-poly shapes with few-constraints, the oscillations for gait like motion can be modified on the fly to create steered motion for navigating a virtual world.

V. Discussion

While this paper has focused on a soft-body system, combining our approach with an underlying rigid-body skeleton (hybrid technique) would open the door to further advantages (i.e., the explicit injection of key-frame motions). For example, a motion capture method would control a rigid-body skeleton from which joint torques are calculated to mimic the motion. However, the joint torques are adjusted based on the environment and model’s state (e.g., balance). Adding an active soft-body system on top of the rigid skeleton - changing the overall centre of mass and injecting rhythmic motions into the movement, such as, breathing and swaying, to produce an animation that is closer to what we see in real-world organic creatures. While the model is decomposed of ‘elements’, it also opens the door to subdivision and fractured motion (e.g., an object that is able to split into smaller soft-body elements, each possessing their own individual motion mechanics). The subdivided mesh remains fixed, however, an area of further investigation would be the dynamic adaptation of the resolution as the character mesh deforms adding and removing extra detail where needed.

In summary, the technique in this paper presents a number of implementation difficulties in practical applications. For example, without sufficient constraints (i.e., addition structural, sheer, and bending constraints), would result in the mesh being unable to support itself and the deformations would be rough and coarse with abrupt and sharp edges. However, our technique can be combined with different model reduction control methodologies, to exploit the computational power of the GPU and help reduce the complexity and computational limitations for more detailed tasks/geometry.

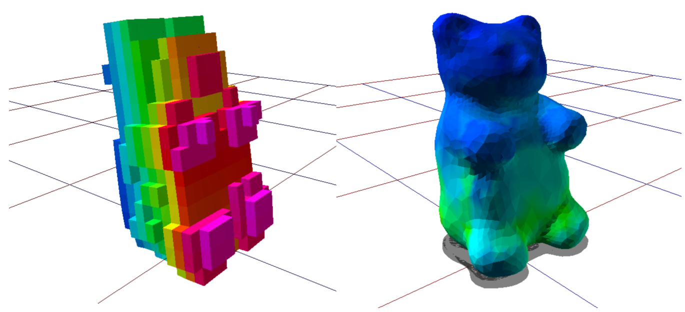

Figure 8. **Gummy-Bear Coarse Voxel Mesh** - A coarse over-mesh decomposed of voxels allows provides a computational speed-up.

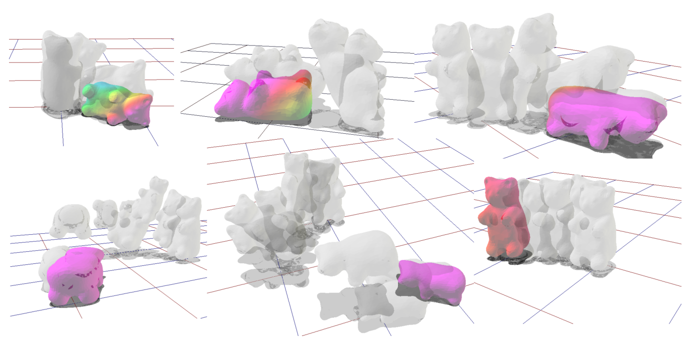

Figure 9. **Gummy-Bear** - Training and deforming the constrains of a gummy-bear mesh to achieve targeted motions, such as, balanced hopping or forward crawling motions. Through experimentation, we are able to create a diverse assortment of solutions, e.g., simple wiggling, bouncing, and shuffling.

VI. Conclusion

Internal forces cause deformations and ultimately structural changes that animate the model. External contacts with the environment provide reactive collision and contact forces that enable the soft-body system to explore its virtual world. We have reviewed and explored a number of implementation factors, such as, multi-resolution meshes, volume conservation, and animation control, using search driven fitness optimization algorithms in combination with artistic intervention and key-frame data. The model forms the basis of other hybrid systems that mix rigid and soft-body systems, such as, muscles and skin.

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