REAL-TIME VIRTUAL CABLES BASED ON KINEMATIC SIMULATION

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ABSTRACT

We present an algorithm for the real-time simulation of virtual cables using inverse kinematics. A cable is modeled by consecutive cylinder segments of equal size. The segments are connected by ball joints. At every joint there is a spiral spring acting against the excursion of the joint. Given a start and an end position of the cable, the algorithm calculates the shape of the cable that leads to minimal total energy. The total energy is the sum of the potential energies of the segments and the elastic energies of the springs. First, the algorithm calculates a cable with minimal total energy consisting of two segments. This is taken as a starting basis for the computation of a cable consisting of four segments. At each following step, the number of segments is doubled and a new shape of the cable is calculated based on the solution of the previous step. The great advantage of this approach is the easy accommodation of the solution exactness to the available computation time. If the user of the VR application is moving the cable, he gets a fast but rough feedback. If he stops moving it, he/she gets an exact shape.

Keywords: Virtual Reality, simulation, deformable objects, kinematic, springs, spline-like objects.

1. INTRODUCTION

Virtual Reality (VR) is used in different fields of applications. A very well-known application is the presentation of CAD construction data of cars. These VR scenes can appear very realistic. If a viewer wants to deform the virtual driver's seat and it keeps its original shape, the application is not really immersive. A high visual realism can only be achieved with physical simulations integrated in VR. The requirements on simulations in VR are different than those for animation. In calculating animations, time constraints are not very strict, while the time for calculations in VR is strongly limited. These simulations have to work in real-time. The calculation of the body deformation has to take just as long as the real deformation. Under these circumstances we make compromises regarding the physical correctness. However, if the simulation is to generate realistic visual results, the virtual bodies should not differ from the real bodies in the substantial characteristics. Mechanical engineering companies want to use virtual reality not only for design studies and presentations but also for the verification and training of assembly-disassembly procedures. One of those procedures is the installation of electrical wiring. A virtual cable should appear as realistic as possible. Like a real cable it should modify its length only a little. In other fields of research, this tiny modification of length is the object of interest; in the case of installation and removal in VR it is inessential. The cable has a constant length for the mechanic, who fits the cable into the car body. For this kind of application we have developed a procedure for fast cable deformation with constant cable length.

2. RELATED WORK

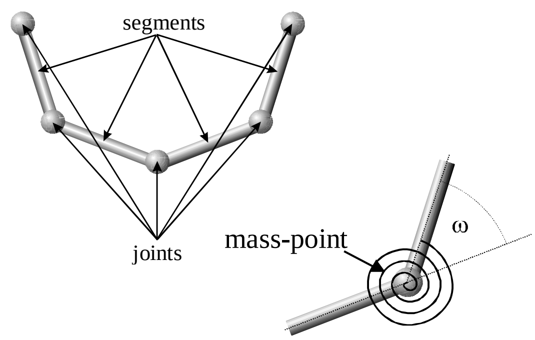
The simulation of flexible bodies has been a topic in the field of computer graphics for more than ten years. There is a large number of interesting work about the animation of cloths and muscle movements [Volino95][Baraff98]. The simulation of flexible bodies will be used not only for off-line animations but also in real-time virtual worlds.

Since the mid-nineties the simulation of anatomical structures has been used for the training of the medical personnel [Müller99]. Most simulations of flexible bodies use only a few basic simulation algorithms. Remion, Nourrit and Gilard used a spline-based procedure for their cloth simulations [Rémion99]. The disadvantage of using splines for the cable simulation is the variable length. Remion et al. added a numerical integration to the spline based simulation procedure and used it for the calculation of the form of the cottons. A numerical integration is also used by the mass-spring system. In this method, a number of parameters control the simulation. An inauspicious choice of parameters can initiate a divergent progression of the simulation. The mass-spring system is very often used to simulate flexible bodies, because it is easy to implement. Miller used it for the simulation of snakes and worms, and his results look very good [Miller91]. The mass-spring system simulates only elastical systems, thus it is impossible to obtain a constant length during the simulation. By using a finite-element method, a divergent progression of the simulation does not occur. Physical attributes like weight and rigidity can be calculated more exactly than in the mass-spring system. Still, the finite element method cannot guarantee length invariance. A software product, based on [Belytschko77], uses a finite element method for the simulation of cable and hoses.

Another simulation method is the inverse kinematics on joint chains. This method is not only popular for articulated-figure animation [Gleicher98]. Singh and Fiume used it to animate the deformations of 2D-bodies [Singh98]. This has led to our idea to develop a simulation procedure based on kinematics, because it is an effective way to ensure a constant length. With this method the physical characteristics like weight and rigidity are not considered. The Cyclic-Coordinate Descent method [Welman93] is an iterative procedure, which can compute inverse kinetics problems very fast. It seemed to be the right method to solve our problem. This procedure uses two weighting functions, one to calculate the position and one to calculate the orientation of the joint. One possibility would be to expand the two functions, so that we can simulate the material properties and the influence of gravitation. A second disadvantage is the oscillation of an iteratively simulated object. If the object keeps moving, the simulation will cost a lot of computation time, degrade interactivity and incommodes the user (just imagine a scenario with a lot of cables and all of them oscillate a bit). These are sufficient reasons for use to think about an alternative procedure. The main reason to develop an hierarchical procedure with a smooth transition between the levels is: The resolution of the cable depends on the available computation time, see also chapter 3.

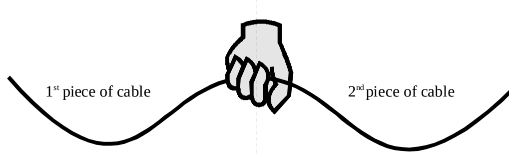
3. THE CONCEPT OF THE ALGORITHM

In order to overcome the shortcomings of the solutions mentioned above when applied to cables, we have developed a novel procedure. The typical characteristic of a cable is that it does not change its length during dragging. To use a kinematically based procedure for the simulation appears to be the most reasonable approach. Dai presents in his book [Dai97] the theoretical possibility to equip the joints with springs, which adds some physical aspects to the simulation. We construct our simulation using Dai's recommendation, see Fig. 3.1.. Using this model, we limit the physical characteristics of the cable to the absolutely necessary. Beside the constant length we consider only the weight and the rigidity of the cable.

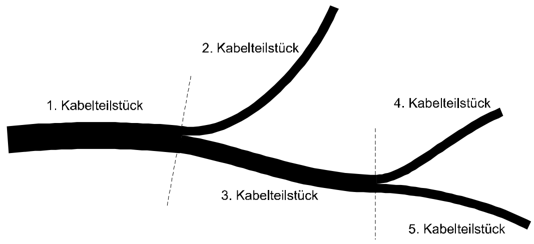


Kinematic on joint chain with a spiral spring at every joint
Figure 3.1

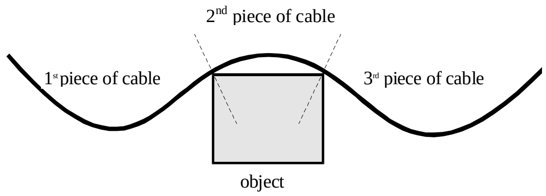
A cable should have an arbitrary length, and for moving it can be touched at any point . It can be shifted around any objects and fastened to them. The form of the cable can become very complex and therefore the calculation is very complex, too. To reduce the complexity of a problem, it is often helpful to divide the starting problem into several less complex sub-problems. Analyzing the application scenarios for such cables, it turned out that each cable can be assembled from several cable sections. The forms of these sections can be simulated independently.



A cable: picked into the center.
Figure 3.2

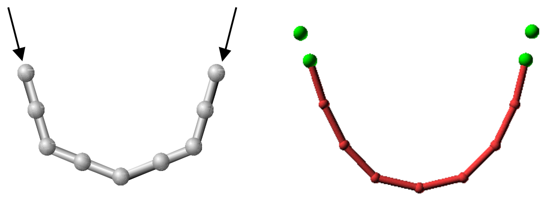


A wiring harness assembled from five sections.
Figure 3.3



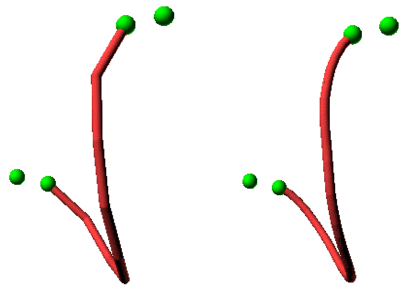
A cable, put over an object.
Figure 3.4.

After the simulation of the individual pieces of a cable, it has to be possible to integrate them to a smoothly coherent cable. We solved this problem by using vectors. They are situated at the start and at the end point of the cable and give its start/end direction and orientation. The described segmentation of the cable influences the conception of the algorithm, but it is not the main focus of this paper. With our approach it is possible to calculate the simulation on different processors in real-time. Real-time in terms of virtual reality applications means a calculation rate of 10-20 cycles per second.



Cable section with “orientation vectors”
(model and snapshot)
Figure 3.5.

For this reason, we use a progressive simulation. While the user moves the cable, a coarser resolution of the cable is simulated. If the user stops the movement, the resolution of the cable becomes refined. By the refinement we receive a smoother surface of the cable.



Cable during the interaction progress and
during a static scene
Figure 3.6.

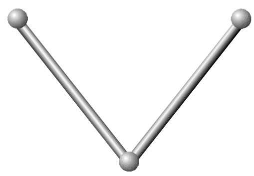
The difficulty of the hierarchical simulation is to realise a gentle transition between the differently refined cable models. In our procedure, transitions are inherently smooth. Using regular kinematics simulation smooth transitions are not guaranteed. Rounding errors let a cable consisting of eight base-points look completely different than a cable consisting of sixteen points.

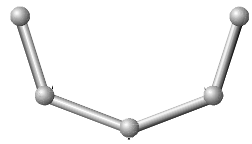
The calculation of flexible deformations with a mass-spring system or the finite-element method is iterative, and because of impreciseness calculations the form of the body oscillates around the final deformations. Thus, the viewer gets the impression that the body’s material is very soft. Our simulation model contains springs, too. So we have the choice to calculate the deformation iteratively or to search for another solution of this problem. We chose the second possibility and found a method to avoid the oscillation. There are three reasons for developing a new kinematics-based simulation procedure:

- Smooth transitions between the different hierarchical simulation steps.
- Improving the handling of gravity and material properties.
- Avoiding oscillation.

4. DESCRIPTION OF THE ALGORITHM

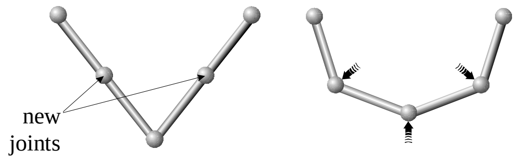
The procedure for the simulation of a piece of cable is substantially based on two algorithms, the calculation of a “two-segment” and the calculation of a “four-segment” cable.





A “two-segment”and a “four-segment”.
Figure 4.1.

Pieces of a cable with 2^n+1 nodal points can be simulated by combining both algorithms. A main characteristic of the procedure is that the simulation of a cable with 2^{n+1}+1 nodes is based on the simulation of a cable with 2^n+1 nodes. It ensures a smooth transition from one resolution level to the higher resolution level. The calculation sequence of the procedure can be described as follows: On the first step we calculate a very coarse approximation of the final state based on two segments. Then the left and the right segments are divided. In the center of every segment we insert a joint. Now the node in the center has to be shifted until the cable gets the minimal energy.

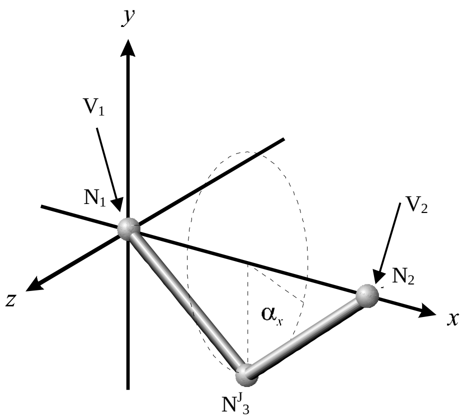


Simulation process of a "four-segment" cable
Figure 4.2.

To calculate a piece of cable consisting of eight segments we successively simulate subranges of four segments. This way, the simulated areas interact with each other. To compute an accurate result, the partial simulation would have to be repeated very often. Our experiment shows in this case that three four-segment calculations suffice. The correct order of simulation is very important. Good visual results are acquired by the sequence in figure A.1.. After this general discussion of the procedure, we describe the two-segment optimization and four-segment optimization in more detail.

TWO-SEGMENT CALCULATION

Each piece of a cable is defined by the position of its first point (N_1), by the position of its last point (N_2), and by its length (l). Its form is affected by the beginning vectors (v_1 and v_2) (see Fig. 4.3). The angle ω between the two segments (see Fig. 3.1.) is fixed by the length of the cable. The joint (N^J_3) can be put on each position within the circular path as shown in Fig. 4.3. Now we have to search the position of N^J_3 where the two-segment cable takes the minimal energy state. Our procedure looks for this position with a numerical search function.



Drawing of a two-segment, with all
Positions N^J_3 can take.
Figure 4.3.

The energy of the two-segment cable is the sum of the potential energies of the segments, calculated with (4.1.), and the elastic energies of the springs, calculated with (4.2.).

Potential energy: $$E_{Pot} = mgh \qquad (4.1)$$

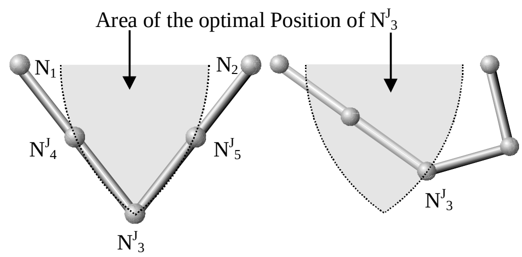
with m: mass
g: gravity
h: relative height of the joint

Elastic energy: $$E_{Spring} = \frac{1}{2} f\omega^2 \qquad (4.2)$$

with f: spring constant
ω: angle between the segments

FOUR-SEGMENT CALCULATION

The four-segment calculation is based on the two-segment calculation. In both segments we insert a joint. If N^J_3 gets a new position, the positions of N^J_4 and N^J_5 are defined by the two-segment calculation. Our goal is to find the position of N^J_3, where the cable takes the minimal energy state.



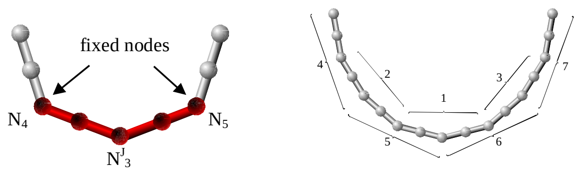
Four-segments cable before and during
the numerical search function
Figure 4.4.

The optimal position of N^J_3 has to be in the intersection of the two spheres that are stretched around N_1 and N_2. The radius of these spheres averages l/2. Again, we search for this position with the numerical search function. In most cases, the optimal position is found after ten iterations of the search procedure. If particular segments are very closely together, more than ten runs may be required.

CALCULATION OF THE WHOLE CABLE

For the simulation of a cable with more than four segments, we also use only the two-segment and the four-segment calculation. As an example, we discuss the simulation of a cable with eight segments. At first we insert four new joints into the calculated four-segment. Now, four-segment subranges will be simulated. You can see the simulation sequence in figure A.1. In the first step, the former joints (N^J_4 and N^J_5) will be regarded as fixed nodes (N_4 and N_5).

They are the start and end points of the first four-segment cable which will be optimised. After this optimisation, N^J_3 becomes the end point of the left segment and the start point of the right segment. These two four-segments cable are calculated afterwards (see Fig. 4.5. and Fig. A.1.).



Eight segments and a simulation sequence
of a 16-segment cable.
Figure 4.5.

Every new iteration of the four-segment calculation corrects the result of the former iterations. More iterations produce a better simulation. To get a visual correct simulation result, the shown sequences are sufficient, as our experiments prove.

5. RESULTS

Our goal was to develop a real-time simulation method for cables in virtual environments that does not change length. Our calculation represents a strong simplification of the real physical behavior, but the visual results give a correct impression. The great advantage of this approach is the easy accommodation of the solutions' exactness to the available computation time.

VISUAL RESULTS

In the following figure, two different pieces of cables are plugged together. By using the "orientation vectors" it is easy to create such a cable. Figures A.5. and A.6. result from shifting the node in the middle of the cable. The transition between the different pieces of the cable is smooth, and the form of the simulated cables appears realistic.

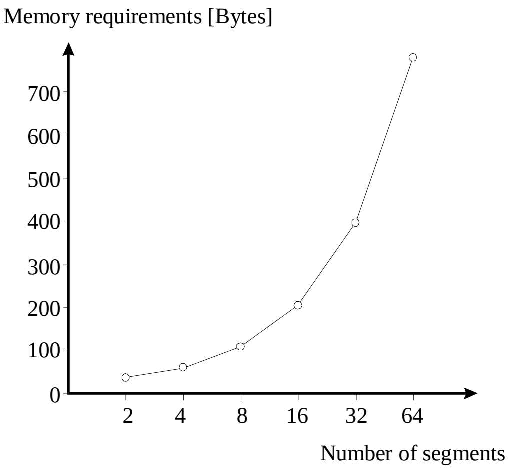
During practical tests, we realised that a cable has to be divided into not less than four segments during the movement. Otherwise, the cable is not flexible enough. If the user stops its movement, the cable segmentation will be increased; 32 segments are sufficient to produce a smooth cable. Fig. A.3. shows how the form of the cable will be influenced by the "orientation vectors". The distribution of mass and the values of the spring constants also influence the form of the cable. In figure A.4. you see three cables. One of them has no mass and another one does not use the springs. These two cables look like a cotton and a chain.

COMPUTATION TIME

It is difficult to determine the computation time, because it depends on the form of the cable. To get an impression of the calculation rate, we measured the speed of some test cases. We measured only the pure calculation time on one processor; the rendering time is not included . In practical tests we found out that with computing times up to 200 ms, a continuous operation is still possible. Two 16-segment cables could be interactive moved on a Octane.

MEMORY REQUIREMENTS

The algorithm needs only a minimum of memory. Only the current positions of the joints will be stored. By n allocation steps of the model we get 2^n segments and 2^n+1 joints. Every joint needs three coordinates. Thus, the total requirement is $(2^n+1)*3*4$ bytes. Additionally, variables like mass, spring constant and "beginning vectors" has to be added, but still the memory complexity is O(n).



Memory requirements
Figure 5.1.

6. CONCLUSION AND FUTURE WORK

This paper reports on an algorithm for fast simulation of the deformation of flexible, length-preserving cables. The implementation and the test that we performed demonstrate the advantages of this approach. To integrate a cable into virtual worlds, a collision detection has to be implemented. Both the self-collision and the collision with other objects has to be detected and analysed. In this context, we think about the integration of force feedback. For training of medical personnel tactile feedback is very important. A possible scenario is the simulation of sewing.

Another goal will be the optimisation of the algorithm. The parallelisation of the calculation of two-segments and four-segments cables is a possible way. A further extension of the cable functionality would make them appear even more realistic. Twisting the cable is not yet possible with our model. This deficiency can be balanced by using additional springs.

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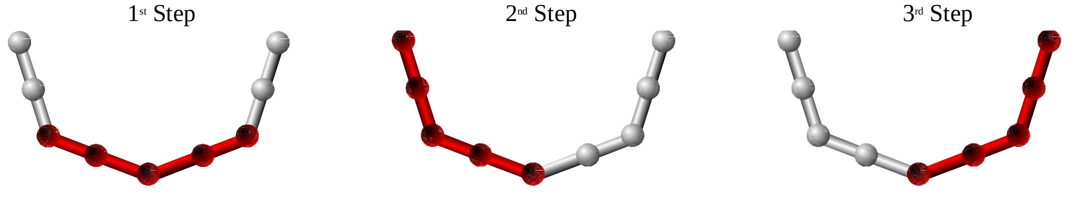

The sequence in which a eight-segment cable is simulated
Figure A.1.

Octane CPU Mips R10000 250 MHz, 100 values, milliseconds						
number of segments	2	4	8	16	32	64
best case	1	10	60	120	170	260
average case	1	20	90	160	230	330
worst case	10	120	260	360	430	520

Octane CPU Mips R10000 250 MHz, 100 values, milliseconds						
number of segments	2	4	8	16	32	64
best case	1	10	60	120	170	260
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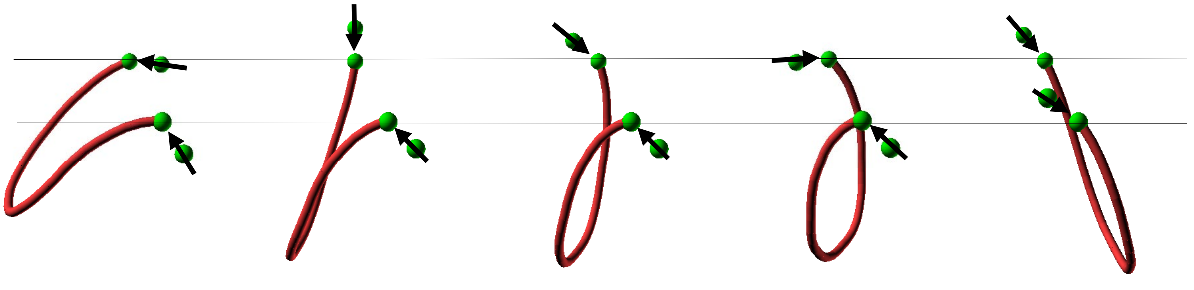
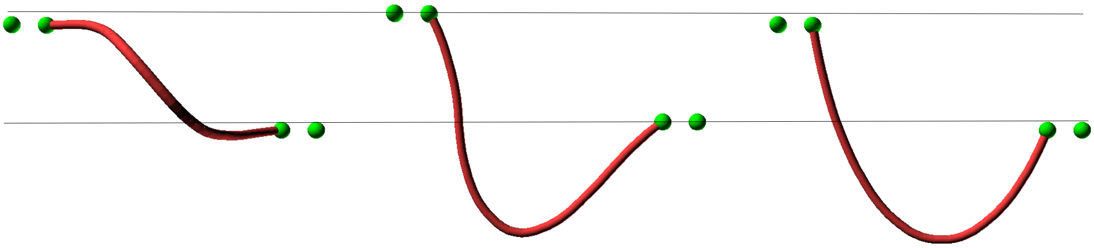
Computation time
Table A.1.

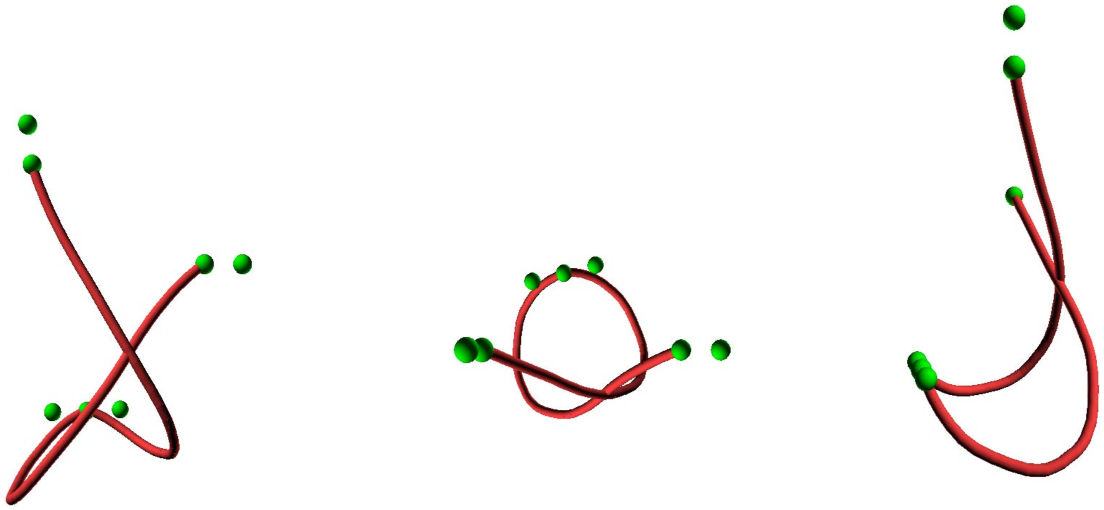


The influence of the orientation vectors
Figure A.2.

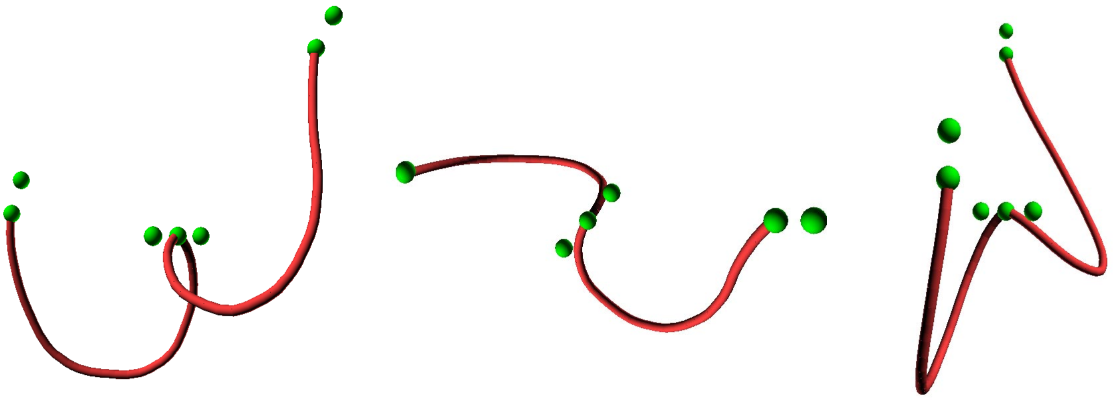


without mass normal without springs

Cables simulates with different material properties
Figure A.3.



Two connected cables seen from different positions
Figure A.4.



front down back

Two connected cables seen from different positions
Figure A.5.