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Scuola di Scienze Matematiche Fisiche e Naturali  
Corso di Laurea Magistrale in Informatica



UNIVERSITÀ  
DEGLI STUDI  
**FIRENZE**

B-SPLINE METHODS FOR THE DESIGN OF  
SMOOTH SPATIAL PATHS WITH OBSTACLE  
AVOIDANCE

METODI B-SPLINE PER IL DISEGNO DI PERCORSI  
REGOLARI IN AMBIENTI TRIDIMENSIONALI  
CONTENENTI OSTACOLI

Tesi di Laurea Magistrale in Informatica

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Luglio 2016, Anno accademico 2015/16

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## ABSTRACT

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*Path planning* problem consists in finding an interpolating curve between two points in a scene with obstacles. It has significant applications in robotics and scientific visualization. It is important to find a curve with certain qualities of smoothing, thus we focus on the curve fairing. Furthermore, for the representation, we use B-spline curves that are an affirmed standard in Computer-Aided Design (CAD) and Computer-Aided Geometric Design (CAGD).

We design different algorithms to solve the problem and we present their complexity analysis. The resulting work is highly interdisciplinary: we address a mixed approach, analytical and stochastic.

We realize an application in Python using Visualization Tool Kit (VTK) for the visualization that implements the presented algorithms. Finally, we systematically test the application with different scenarios.

*Dedicated to a future of elevation for the human condition.*

*I hear and I forget.  
I see and I remember.  
I do and I understand.*

— Confucius

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## ACKNOWLEDGMENTS

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I would like to express my sincere gratitude to my coordinator Prof. Alessandra Sestini and my advisor Ph.D. Carlotta Giannelli for their patience and the priceless revision work. I want to thank them also for introducing me to this research area and for their guidance through the development of this project.

I also would like to thank all the professors for contributing, with their passion, to make me a better person and for instilling in me the passion for knowledge. Among them, a special mention goes to Prof. Pierluigi Crescenzi for the advice that he gave me for complexity analysis, Prof. Mariacecilia Verri for the advice on the algorithms, Prof. Gregorio Landi and Prof. Franco Bagnoli for introducing me to stochastic methods.

I would like to thank all my friends for being life companions and for all the adventures that we had and we will continue to have.

A special loving thank goes to my parents Mauro and Rosa, and to my brother Simone, for patiently contributing to sustain me all this years, for tangible and intangible needs.

Finally, last but not least, I want to thank Federica, the woman of my life, for making the world a worthier place to live in and for the unconditional love that she gives to me everyday (and also for helping me to make this text more readable).

*Stefano Martina*



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# 1

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## INTRODUCTION

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The design of *motion planning* strategies plays a fundamental role in different applications, from robotics to scientific visualization. *Path planning* problem is more specific, it consists in identifying paths that do not intersect any obstacle.

In this project we are interested in generating smooth paths. Smoothness is a desirable property that is frequently presented in literature for the planar case. Consider, for instance, the works [28], [18], [27] and [16]. On in the latter in particular, they used Pythagorean Hodograph (PH) curves that have interesting features for the Computer-Aided Manufacturing (CAM) field [13].

In regards of spatial path planning, the smoothing problem is less covered in literature. For instance, in [20] it is not clear how a smooth path is obtained from the initial polynomial chain. In [40] the smoothness is considered, but the method is not optimal because it consists in alternating smoothing and obstacle-checking phases until an admissible solution is obtained. Other works, like [2] and [25], use stochastic methods to achieve smoothness.

B-spline curves are a reference standard in CAD and CAGD [21][22][12][15]. Thus, we decide to develop a 3D path planning application using this kind of curves, as [40] do. However, as earlier mentioned, [40] uses a *try and check* approach to the curve smoothing, we present a method that finds a smooth curve on the first attempt instead.

The considered topic is highly interdisciplinary. In fact we integrate in this project an extended set of competencies acquired during the courses. We apply notions of *linear algebra* for the collision checks; *numerical analysis* for the curves design; *computational geometry*, *graph theory*, *probability* and *algorithm theory* for the algorithms design; and, finally, *theoretical computer science* for cost analysis.

We focus on finding a trade-off between having a short curve, a smooth curve, and keeping the time complexity low. Different solutions are explored, with different qualitative effects on the curve.

Regarding the scene representation, different kinds of polyhedral obstacle are considered.

A framework in Python is developed using VTK for the graphic output. We use a roadmap method based on Voronoi Diagrams (VDs) to create a graph (details in Section 5.1.1) that is the base structure for the project. Using such structure, three different solutions are presented.

1. The first method benefits from the Convex Hull Property (CHP) of B-spline curves (Section 3.2.1). A transformation is applied on the graph such that every path in it can be used as a control polygon for an obstacle-free curve (Section 5.1.2). Therefore, the algorithm selects the shortest path in the transformed graph and builds the curve on it (Section 5.2.1).
2. The second method still benefits from the CHP, but it picks the shortest path directly in the base graph. If violations of the CHP emerge in it, then rectification measures are taken (crefsec:inter2).
3. The third method uses a probabilistic approach. Starting from the shortest path in the original graph, it performs a simulated annealing optimization (Section 3.4.3) that converges in a state where we have an optimal trade-off between having a short curve, and low curvature and torsion peaks (Section 5.6).

This document consists of three parts. The first (Part I) is dedicated to the state of the art: we provide a survey of different topics and algorithms related to *motion planning*.

The second part (Part II) is committed to describing all the different parts of the algorithm. In detail:

- Chapter 3 gives to the reader all the necessary notions to understand the rest of the chapter;
- Chapter 4 describes how the environment and the resulting curve are represented;
- Finally in Chapter 5 we describe how to obtain the basic structures (Section 5.1), how to avoid the obstacles using the three methods described before (Section 5.2), and how to improve the obtained curve simplifying the control polygon (Section 5.5), increasing the

curve degree (Section 5.3) and changing the B-spline knot vector (Section 5.4).

The third part (Part III) describes the instruments used to implement the algorithms (crefcha:codeStructure) and presents a series of tests with different scenes and configurations (Chapter 7) with their conclusions (Chapter 8).

In conclusion, Appendix A contains all the source code of the application.



Part I  
STATE OF THE ART



# 2

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## MOTION PLANNING

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The problem of *motion planning* consists in determining a set of low level tasks, given an high level goal to be fulfilled [7]. For instance, a classic motion planning problem is the *piano movers'* problem that involves the motion of a free flying rigid body in the 3-dimensional space from a start to a goal configuration by applying translations and rotations and by avoiding collisions with a set of obstacles [7][26]. Motion planning finds applications in different areas, like robotics, Unmanned Aerial Vehicles (UAVs) [17] and autonomous vehicles [30]. These are the most famous applications but it finds utilization also in other less common areas like motion of digital actors or molecule design [7].

Initially, the term motion planning referred only to the translations and rotations of objects, ignoring the dynamics of them, but lately research in this field started considering also the physical constraints of the object to be moved [26]. Usually, the term *trajectory planning* is used to refer to the problem of taking the path produced by a motion planning algorithm and determine the time law for moving a robot on it by respecting its mechanical constraints [26].

An important concept for motion planning problems is the *state space*, that can have different dimensions, one for each degree of freedom of the robot. It can be a discrete or a continuous space [26]. We can call the space state  $S$  and, considering that there are obstacles or constraints on the scene, we can call  $S_{\text{free}} \subseteq S$  the portion of the state space such that all its configurations are admissible. On this space state we have special states  $s \in S$  and  $e \in S$  for the desired *start* and *end* configurations, respectively.

Another concept is the geometric design of the scene and the actor. The obstacles can be represented as convex polygons/polyhedrons, or also as more complex shapes [26].

Furthermore, it is important to define the possible admissible transformations of the body, if it is possible only to translate and rotate it or if

its motion is composed of rigid kinematic chains or trees or if it is even possible to have not rigid transformations (flexible materials) [26].

## 2.1 PROBLEM TYPES

Many different problems related to motion planning have been introduced in literature. In this section we present a short survey of the most relevant problems in order of increasing complexity. Refer to [17] for details.

**POINT VEHICLE** The body of the object to be moved is represented as a point in the space. Thus the state space  $S$  consists in the euclidean space  $\mathbb{E}^2$  if we consider land vehicles or  $\mathbb{E}^3$  if we consider aerial vehicles.

**POINT VEHICLE WITH DIFFERENTIAL CONSTRAINTS** This problem extends the point vehicle's problem by adding the constraints of the physical dynamic. For instance, constraints on acceleration, velocity, curvature, etc... when we want to model a real vehicle (whose shape is still approximated with a point).

**JOGGER'S PROBLEM** This kind of problems concerns the dynamic of a jogger that has a limited field of view. Consequently, in this case, we do not have a complete view of the scene and the path is updated as soon as the knowledge of the scene increases.

**BUG'S PROBLEM** This problem is an extreme case of the jogger's problem with a null field of view. Thus the scene updating can be done only when an obstacle is touched.

**WEIGHTED REGIONS' PROBLEM** This problem considers some regions of the space as more desirable than others, rather than contemplate completely obstructive obstacles. For instance, this is the case of finding a path in an off-road environment where the vehicle can move faster on certain terrains and slower over different configurations.

**MOVER'S PROBLEM** The vehicle is modeled as a rigid body, thus, we need to add the dimensions for the spatial rotation of the body to the state space.

**GENERAL VEHICLE WITH DIFFERENTIAL CONSTRAINTS** This problem combines the *mover's problem* and the *point vehicle with differential constraints* by adding to the mover's problem the physical constraints on the motion dynamic.

**TIME VARYING ENVIRONMENTS** These problems regards moving obstacles.

**MULTIPLE MOVERS** This problem considers more than one vehicle. We need to manage different paths and the problem of avoiding possible collisions between different movers. As a matter of fact, we have to avoid collisions between the paths followed by different movers only if the collision point is reached by the movers simultaneously.

## 2.2 ALGORITHM TYPES

We can divide the algorithms for motion planning in different types taking into account the specific problem they resolve. The algorithms belonging to a certain type can be further divided in different categories. For more details on the different algorithms see [17] and [7].

### 2.2.1 Roadmap methods

This kind of algorithms reduces the problem of motion planning to graph search algorithms. The state space is approximated with a certain graph in order to find a solution in terms of a polygonal chain.

#### 2.2.1.1 Visibility graph

The visibility graph is one of the most known roadmap methods. The nodes of the graph correspond to the vertices of each polygonal obstacles in the considered scenario. The edges of the graph correspond to linear segments between pair of vertices that do not intersect any obstacle. The Dijkstra's algorithm is then usually considered to compute the *shortest path* between two vertices of the graph [10]. Note that the shortest path associated to the visibility graph in a planar configuration is the absolute shortest path from the start to the goal position with respect to the considered scenario, see e.g., [8]. While this method finds the optimal solution (with respect to a *distance* criterion) in the planar case, it does not properly scale in a 3-dimensional setting.

### 2.2.1.2 Edge sample visibility graph

The edge sample visibility graph is an extension of the visibility graph method to the 3-dimensional case. The main idea consists in distributing a discrete set of points along the edges of the obstacles by considering a certain density. The visibility graph and the related shortest path of this configuration are then computed, but the corresponding solution is not as optimal as in the planar case.

### 2.2.1.3 Voronoi roadmap

This method builds a graph that is kept equidistant to the obstacles, using VDs as base method for constructing it. We discuss VDs in detail in Section 3.3 and Voronoi roadmap method in Section 5.1.

### 2.2.1.4 Silhouette method

This method was developed by Canny [6]. It is not useful for practical uses but just for proving algorithmic bounds because it is proven to be complete in any dimension. It works sweeping the space with a line (plane in 3-dimensional space) perpendicular to the segment between  $s$  and  $e$  and building the shape of the obstacles when the sweeping line intersects them.

## 2.2.2 Cell decomposition

This method decomposes  $S_{\text{free}}$  in smaller convex polygons - i.e. trapezoids cylinders or balls - that are connected by a graph, then searches a solution in such graph. A cell decomposition method can be exact or approximate, the former kind operates occupying all  $S_{\text{free}}$  with the graph structure, the latter one can occupy also portions of  $S \setminus S_{\text{free}}$  or all  $S$ . Then the various polygons are labelled as obstacle-empty, inside obstacle or partially occupied by obstacles.

## 2.2.3 Potential field methods

This kind of methods operates assigning a potential field on every region of the space, the lowest potential is assigned to the goal point  $e$  and a high potential value is assigned to the obstacles. Then the path is calculated as a trajectory of a particle that reacts to those potentials, it is repelled by the obstacles and attracted by the end point.

#### 2.2.4 Probabilistic approaches

This kind of methods uses probabilistic techniques for exploring the space of solutions and finding a good approximation of the optimal solution. In our project we provide also a mixed roadmap-probabilistic method, see Section 3.4 and Section 5.6 for further details.

#### 2.2.5 Rapidly-expanding Random Tree (RRT)

This method operates by doing a stochastic search, starting from the reference frame of the object to be moved and expanding a tree through the random sampling of the state space.

#### 2.2.6 Decoupled trajectory planning

This kind of algorithms operates in a two-step way. First a discrete path through the state space is found, then the path is modified to adapt it to the dynamics constraints - i.e. the trajectory is constructed.

#### 2.2.7 Mathematical programming

This method manages the trajectory planning problem as a numerical optimization problem, using methods like nonlinear programming to find the optimal solution.

### 2.3 PATH PLANNING

In our project we concentrate on a subset of the motion planning problem, the *path planning* problem that consists [7] in determining a parametric curve

$$\mathbf{C} : [a, b] \subset \mathbb{R} \rightarrow \mathcal{S}$$

such that  $\mathbf{C}(a) = \mathbf{s}$  coincides with the desired starting configuration,  $\mathbf{C}(b) = \mathbf{e}$  the desired end configuration and the image of  $\mathbf{C}$  is a subset of  $\mathcal{S}_{\text{free}}$ , in other words

$$\mathbf{C}(u) \in \mathcal{S}_{\text{free}} \quad \forall u \in [a, b].$$

In principle the space of the states  $\mathcal{S}$  can be of any dimension, for instance if we focus on the piano movers' problem the state is composed

by 3 dimensions for the position and other 3 dimensions for the rotation of the object [26]. Also the curve  $\mathbf{C}$  can be parameterized in any way.

In this project we concentrate on the problem of path planning where the state space is  $S = \mathbb{E}^3$  and the curve is parameterized in  $[0, 1]$ . Thus we find a curve from one point  $s \in \mathbb{E}^3$  to another point  $e \in \mathbb{E}^3$  avoiding obstacles. The object that we move is considered just as a point.

Part II  
PROJECT



# 3

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## PREREQUISITES

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### 3.1 SPLINES AND B-SPLINES

A *spline* is a piecewise polynomial function with prescribed regularity on its domain.

More formally we define a spline [9][12][34][33]

$$s : [a, b] \subset \mathbb{R} \rightarrow \mathbb{R}$$

as follows. We have a partition of that interval defined by the *breakpoints*

$$\tau = \{\tau_0, \dots, \tau_\ell\}$$

such that  $a = \tau_0 < \tau_1 < \dots < \tau_{\ell-1} < \tau_\ell = b$ . Such breakpoints define  $\ell$  intervals

$$I_i = \begin{cases} [\tau_i, \tau_{i+1}) & \text{if } i = 0, \dots, \ell - 2 \\ [\tau_i, \tau_{i+1}] & \text{if } i = \ell - 1. \end{cases}$$

It is possible to define the following spaces:

**PIECEWISE POLYNOMIAL FUNCTIONS SPACE**  $P_{m,\tau}$  is the space of the functions that are polynomials of maximum degree  $m$  in each interval  $I_i$  of the partition, formally:

$$P_{m,\tau} = \{f : [a, b] \rightarrow \mathbb{R} \mid \exists p_0 \dots p_{\ell-1} \in \Pi_m \text{ such that} \\ f(t) = p(t), \forall t \in I_i, i = 0 \dots \ell - 1\}$$

where  $\Pi_m$  is the space of the polynomials of degree  $\leq m$ . The dimension of  $P_{m,\tau}$  is

$$\dim(P_{m,\tau}) = \ell(m + 1)$$

because the dimension of  $\Pi_m$  is  $m + 1$ .

**CLASSIC SPLINE SPACE**  $S_{m,\tau}$  is the space of the piecewise polynomial functions of degree  $m$  that have continuity  $C^{m-1}$  in the junctions of the intervals, formally:

$$S_{m,\tau} = P_{m,\tau} \cap C^{m-1}[a, b].$$

The dimension of this space is

$$\ell(m+1) - (\ell-1) \cdot m = \ell + m. \quad (1)$$

**GENERALIZED SPLINE SPACE**  $S_{m,\tau,M}$  is the space of piecewise polynomial functions of degree  $m$  with a prescribed regularity at each breakpoint ranging from  $-1$  to  $m-1$ . The regularity is prescribed by the multiplicity vector

$$M = \{m_1, \dots, m_{\ell-1}\}, \quad m_i \in \mathbb{N}, \quad 1 \leq m_i \leq m+1$$

as follows,

$$\begin{aligned} S_{m,\tau,M} = & \{f : [a, b] \rightarrow \mathbb{R} \mid \exists p_0 \dots p_{\ell-1} \in \Pi_m \text{ such that} \\ & f(t) = p(t), \forall t \in I_i, i = 0 \dots \ell-1 \text{ and} \\ & p_{i-1}^{(j)}(\tau_i) = p_i^{(j)}(\tau_i), j = 0, \dots, m - m_i, i = 1, \dots, \ell-1\}. \end{aligned}$$

The dimension of the space is equal to

$$\dim(S_{m,\tau,M}) = \ell(m+1) - \sum_{i=1}^{\ell-1} (m - m_i + 1) = m + \mu + 1 \quad (\mu = \sum_{i=1}^{\ell-1} m_i)$$

and is true that

$$\Pi_m \subseteq S_{m,\tau} \subseteq S_{m,\tau,M} \subseteq P_{m,\tau},$$

in particular:

- if  $m_i = 1$  for all  $i = 1, \dots, \ell-1$ , then  $S_{m,\tau,M} = S_{m,\tau}$ ;
- if  $m_i = m+1$  for all  $i = 1, \dots, \ell-1$ , then  $S_{m,\tau,M} = P_{m,\tau}$ .

### 3.1.1 Truncated-powers basis for classic splines

A truncated power  $(t - \tau_i)_+^m$  is defined by

$$(t - \tau_i)_+^m = \begin{cases} 0, & \text{if } t \leq \tau_i \\ (t - \tau_i)^m, & \text{otherwise.} \end{cases}$$

It is possible to demonstrate that the functions

$$g_i(t) = (t - \tau_i)_+^m \in S_{m,\tau}, \quad i = 1, \dots, \ell - 1$$

are linearly independent, and that the set

$$1, t, t^2, \dots, t^m, (t - \tau_1)_+^m, \dots, (t - \tau_{\ell-1})_+^m$$

forms a basis for the classic spline space [9]. Then a generic element  $s \in S_{m,\tau}$  can be expressed as follows,

$$s(t) = \sum_{i=0}^m c_i t^i + \sum_{j=1}^{\ell-1} d_j (t - \tau_j)_+^m \quad \begin{aligned} c_i &\in \mathbb{R}, \quad i = 0, \dots, m \\ d_j &\in \mathbb{R}, \quad j = 1, \dots, \ell - 1. \end{aligned} \quad (2)$$

### 3.1.2 B-splines basis for classic splines

B-splines are a specific basis which can be alternatively used to represent any generalized spline [9][12][34][33]. In this paragraph, however, we consider only their definition to generate the classic spline space  $S_{m,\tau}$ . Furthermore in some textbooks, for notational convenience, the  $order = m + 1$  is considered.

For defining the B-splines [9] we need to extend the partition vector  $\tau = \{\tau_0, \dots, \tau_\ell\}$  with  $m$  knots to the left and  $m$  to the right, thus we define a new vector, usually called *extended knot* vector,

$$\tau = \{t_0, \dots, t_{m-1}, t_m, \dots, t_{n+1}, t_{n+2}, \dots, t_{n+m+1}\}$$

such that

$$t_0 \leq \dots \leq t_{m-1} \leq \overset{\equiv \tau_0 \equiv a}{t_m} < \dots < t_{n+1} \leq \overset{\equiv \tau_\ell \equiv b}{t_{n+2}} \leq \dots \leq t_{n+m+1}.$$

Since  $\tau$  has  $\ell + 1$  elements, we can calculate the value of

$$n = \ell + m - 1.$$

Thus the dimension of  $S_{m,\tau}$ , for Eq. (1), is

$$\dim(S_{m,\tau}) = \ell + m = n + 1$$

The  $n + 1$  basis  $N_{i,m+1}(t)$  of the B-splines of degree  $m$  are defined, for  $i = 0, \dots, n$ , by the recursive formula:

$$N_{i,1}(t) = \begin{cases} 1, & \text{if } t_i \leq t < t_{i+1} \\ 0, & \text{otherwise} \end{cases} \quad i = 0, \dots, n + m$$

$$N_{i,r}(t) = \omega_{i,r-1}(t) \cdot N_{i,r-1}(t) + (1 - \omega_{i+1,r-1}(t)) \cdot N_{i+1,r-1}(t) \quad \begin{aligned} i &= 0, \dots, n + m - 3, \\ r &= 2, \dots, m + 1 \end{aligned}$$

where

$$\omega_{i,r}(t) = \begin{cases} \frac{t-t_i}{t_{i+r}-t_i}, & \text{if } t_i \neq t_{i+r} \\ 0, & \text{otherwise.} \end{cases}$$

Then any function  $s \in S_{m,\tau}$  can be expressed also as a linear combination of B-splines,

$$s(t) = \sum_{i=0}^n v_i N_{i,m+1}(t) \quad , v_i \in \mathbb{R}, i = 0, \dots, n. \quad (3)$$

### 3.1.3 Spline curves

A *spline curve* in the affine space  $\mathbb{E}^d$  is the image of a parametric vector function  $S : [a, b] \rightarrow \mathbb{E}^d$  whose components are all splines belonging to a fixed spline space  $S_{m,\tau}$ , for  $d = 3$

$$S(u) = \begin{bmatrix} x(u) \\ y(u) \\ z(u) \end{bmatrix}. \quad (4)$$

$S(u)$  can be written as follows in the truncated-powers basis Eq. (2) replacing the coefficients  $c_i$  and  $d_j$  with points

$$S(u) = \sum_{i=0}^m c_i \cdot t^i + \sum_{j=1}^{\ell-1} d_j \cdot (u - \tau_j)_+^m \quad , c_i \in \mathbb{E}^d, d_j \in \mathbb{E}^d \quad (5)$$

$$i = 0, \dots, m; j = 0, \dots, \ell - 1.$$

This representation is not practical because there isn't an intuitive correlation between the points  $c_i, d_j$  and the curve itself. Moreover the determination of an interpolant to assess argued points in  $\mathbb{E}^d$  is not a well conditioned problem if this form is adopted [9]. To overcome those drawbacks the *B-splines basis* is adopted (Section 3.1.2).

We can apply control vertices to a spline expressed with the B-spline basis as in Eq. (3) replacing the coefficients  $v_i$  with points, in this case  $S(u)$  is represented as follows

$$S(u) = \sum_{i=0}^n v_i \cdot N_{i,m+1}(u) \quad , v_i \in \mathbb{E}^d, i = 0, \dots, n. \quad (6)$$

The representation of Eq. (6) is more convenient than the previous one (Eq. (5)) because the curve  $S(u)$  roughly follows the shape given by the

points  $v_i$ . Those points are called *control vertices* because they are used to control the curve shape. Conformally the polygon they define is called *control polygon*.

### 3.2 B-SPLINES CURVES PROPERTIES

In this section we describe some properties of B-spline curves that we use for the development of the project.

#### 3.2.1 Convex Hull Property (CHP)

The Convex Hull Property (CHP) states that a B-spline curve  $S(u)$  of order  $m$ , defined by the control polygon  $v_0, v_1, \dots, v_n$ , is contained inside the union of the convex hulls composed of  $m+1$  vertices of the control polygon [12]. If we call  $\text{Conv}(w_0, w_1, \dots, w_j)$  the convex hull of the vertices  $w_0, w_1, \dots, w_j$  then we have

$$\begin{aligned} C_0 &= \text{Conv}(v_0, v_1, \dots, v_m) \\ C_1 &= \text{Conv}(v_1, v_2, \dots, v_{m+1}) \\ &\dots \\ C_{n-m} &= \text{Conv}(v_{n-m}, v_{n-m+1}, \dots, v_n) \end{aligned}$$

and the area where  $S$  is contained is

$$C = C_0 \cup C_1 \cup \dots \cup C_{n-m}$$

or in other words must be true

$$S(u) \cap C = S(u) \quad \forall u \in [a, b]$$

whatever is the partition vector.

In Fig. 1 an example of control polygon is visible, together with the region  $C$  (in cyan) where an associated quadratic B-spline curve is located.

Note that the CHP holds also in 3-dimensional space - i.e. a quadratic B-spline in 3-dimensional space is contained inside a flat surface composed by the union of triangles. From degree 3 the area where  $S$  is contained is not plane anymore because it is composed by the union of solid polyhedrons.

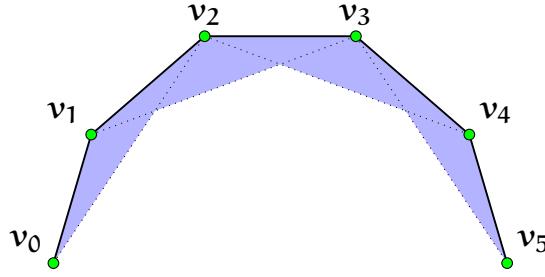


Figure 1.: Convex hull containing B-spline of degree 2

### 3.2.2 Aligned vertices

Because control polygons with sequences of aligned vertices have been adopted in some parts of this project, in this section their specific effect on the curve shape is analyzed.

We can have the following situations:

**m ALIGNED CONTROL VERTICES** If  $m$  control vertices  $v_i, \dots, v_{i+m-1}$  of the control polygon are on the same line then the curve  $S$  touches the segment joining those vertices.

**$m+1$  ALIGNED CONTROL VERTICES** If  $m+1$  control vertices  $v_i, \dots, v_{i+m}$  of the control polygon are on the same line then a polynomial arc of the curve  $S$  lays on the segment joining those vertices.

### 3.2.3 Smoothness

A function is said smooth of class  $C^d$  if it is possible to calculate the  $d$ -th derivative of it and if such derivative is continue. A function  $f$  that is not continue is said to be of class  $C^{-1}$ , a function that is continue until derivative  $d$  is said to be of class  $C^d$ , a function that is always continue for every derivative is said to be of class  $C^\infty$ .

A B-spline curve of degree  $m$  with  $n$  control vertices is composed by  $n-m$  polynomial segments, one for each interval

$$[t_i, t_{i+1}] \quad i = m, \dots, n+1;$$

this means that  $S(u)$  is  $C^\infty$  for

$$u \in (t_i, t_{i+1}) \quad i = m, \dots, n+1.$$

Note that, if we use generalized B-spline curves, an interval  $[t_i, t_{i+1}]$  can also degenerate in just a point if we have a knot multiplicity  $> 1$ , in such case there isn't a polynomial segment. On every breakpoint  $\tau_i$  with  $i = 1, \dots, n+m$  we have that the curve has smoothness<sup>1</sup>  $C^{m-1}$ .

In our project we don't use generalized B-spline curves, thus a curve of degree  $m$  has global smoothness

$$C^{m-1}.$$

### 3.2.4 End point interpolation

In general a B-spline curve with control vertices

$$v_0, \dots, v_n$$

and extended knot vector

$$T = \{t_0, \dots, t_{m-1}, t_m, \dots, t_{n+1}, t_{n+2}, \dots, t_{n+m+1}\}$$

does not necessarily interpolate any control vertex  $v_i$ , neither the first nor the last one. But we are interested in using B-spline for representing paths from one point to another. Hence, it should be a nice feature to have that the curve defined in the domain  $[a, b]$  is shaped such that

$$\begin{cases} S(u) = v_0 & \text{for } u = a \\ S(u) = v_n & \text{for } u = b. \end{cases} \quad (7)$$

We can obtain [9] the conditions of Eq. (7) if we impose

$$t_0 = \dots = t_{m-1} \overset{\equiv a}{=} t_m < \dots < \overset{\equiv b}{=} t_{n+1} = t_{n+2} = \dots = t_{n+m+1}$$

on the extended partition vector  $T$ . In other words

$$T = \{\overbrace{a, \dots, a}^m, t_{m+1}, \dots, t_n, \overbrace{b, \dots, b}^m\}.$$

### 3.2.5 Curvature and torsion

Since we are interested in comparing different curves, we need to recognize if a certain curve is a *good* or a *bad* one. One factor that characterizes

---

<sup>1</sup> If we use generalized B-spline curves, it has smoothness  $C^{m-r}$  where  $r$  is the multiplicity of the knot [12].

a certain curve can be its smoothness (Section 3.2.3) - i.e. a  $C^3$  curve is better than a  $C^2$  curve - but this isn't enough for comparing curves. Usually *curvature* and *torsion* are used for this purpose [11][34]. Both are scalar quantities defined on sufficiently smooth parametric curves for each value of the parameter, and they do not depend on the selected parametrization.

For a generic parametric curve<sup>2</sup>  $\mathbf{S}(u)$  defined for  $u \in [a, b]$  given the notation  $\wedge$  for the vector product and for Eq. (4)

$$\dot{\mathbf{S}}(u) = \frac{d}{du} \mathbf{S}(u) = \begin{bmatrix} \frac{d}{du} \mathbf{x}(u) \\ \frac{d}{du} \mathbf{y}(u) \\ \frac{d}{du} \mathbf{z}(u) \end{bmatrix},$$

we define the curvature  $\kappa(u)$  and, in points with non vanishing curvature, the torsion  $\tau(u)$  as

$$\kappa(u) = \frac{\|\dot{\mathbf{S}}(u) \wedge \ddot{\mathbf{S}}(u)\|_2}{\|\dot{\mathbf{S}}(u)\|_2^3} \quad (8)$$

$$\tau(u) = \frac{\det[\dot{\mathbf{S}}(u), \ddot{\mathbf{S}}(u), \dddot{\mathbf{S}}(u)]}{\|\dot{\mathbf{S}}(u) \wedge \ddot{\mathbf{S}}(u)\|_2} = \frac{(\dot{\mathbf{S}}(u) \wedge \ddot{\mathbf{S}}(u)) \cdot \dddot{\mathbf{S}}(u)}{\|\dot{\mathbf{S}}(u) \wedge \ddot{\mathbf{S}}(u)\|_2}. \quad (9)$$

Equation (8) and Eq. (9) describe completely the behavior of  $\mathbf{S}(u)$  locally for each value of  $u$ . Curvature and torsion have also a geometric interpretation: for each value  $\tilde{u}$  of the parameter  $u$ , the inverse  $\frac{1}{\kappa(\tilde{u})}$  of the curvature is the radius of curvature of  $\mathbf{S}$  at  $\mathbf{S}(\tilde{u})$  - i.e. the radius of the osculating circle tangent in that point.  $\tau(\tilde{u})$  indicates (if  $\kappa(\tilde{u}) \neq 0$ ) how sharply the plane where the curve lies is rotating.

The value of  $\kappa(u)$  can be only non negative, while  $\tau(u)$  is a signed quantity.

Two curves of same smoothness can be compared using the plots of curvature and torsion, in general curves that have lower peaks of  $\kappa(u)$  and  $\tau(u)$  are better than curves with higher peaks.

---

<sup>2</sup> Thus also a B-spline curve.

### 3.2.6 Arc length

Sometimes we are interested in evaluating the length of a generic parametric curve<sup>3</sup>  $\mathbf{S}(u)$  defined for  $u \in [a, b]$ . We can obtain such length, called *arc length*, calculating the integral

$$\int_a^b \|\dot{\mathbf{S}}(u)\|_2 du.$$

We can approximate this value using a discrete tabulation of the curve  $\mathbf{S}(u)$  and an integrating method like the *trapezoidal rule* [31][37].

## 3.3 VORONOI DIAGRAMS

In this section we introduce Voronoi Diagrams (VDs), an important structure used in the project. VDs [8] provide a method to create a partition of the space using distances from a set of input points called *sites*. Formally we have a set

$$S = \{s_0, s_1, \dots, s_n\} \subset \mathbb{E}^d$$

of  $n$  sites in the euclidean space of dimension  $d$ , and we build a set of  $n$  Voronoi *cells*<sup>4</sup>

$$\text{Vor}(S) = \{V(s_0), \dots, V(s_n)\} \subset 2^{\mathbb{E}^d}$$

such that

$$V(s_i) = \{p \in \mathbb{E}^d : \|p - s_i\|_2 < \|p - s_j\|_2 \ \forall s_j \neq s_i\}$$

is the set of the points in  $\mathbb{E}^d$  closer to  $s_i$  than to any other site.

Figure 2 is an example of the VD built on some random sites, the dashed lines in the figure are edges that go to infinite.

The most important algorithm for calculating VDs is the *Fortune's sweeping line* algorithm that builds the diagram in  $\mathcal{O}(n \log n)$  and it is optimal. The algorithm involves building  $\text{Vor}(S)$  incrementally while sweeping the space, see Fig. 3. Every time that the sweeping line finds a site the algorithm creates a parabola using the site as focus and the sweeping line as directrix. Such parabolas, or better the arcs between each intersection of them, constitute the *beach line*. A parabola disappears from the scene

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<sup>3</sup> See Footnote 2.

<sup>4</sup>  $2^{\mathbb{E}^d}$  is the power set of  $\mathbb{E}^d$ , the set of all the subsets of  $\mathbb{E}^d$ .

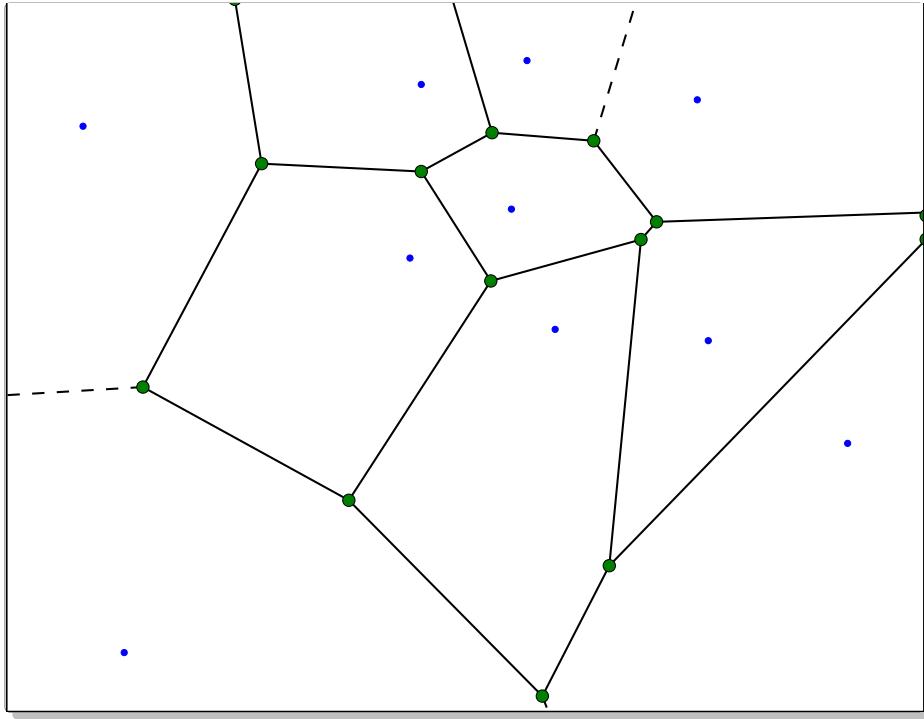


Figure 2.: Example of a VD, dashed lines are infinite edges.

when the associated arc vanishes. The evolution of the intersection points on the beach line constitutes the edges of the VD, and each point where an arc of the beach line disappears constitutes a vertex of the VD. Refer to [8] and [14] for details about the Fortune's algorithm.

One property of VDs is that  $V(s_i)$  can be a closed or an open area - i.e. the edges of the cells can be infinite - it is important to keep this in mind if we want to interpret  $\text{Vor}(S)$  as a graph. In that case the graph will have edges that go to infinite. We call such graph  $G(\text{Vor}(S))$ .

Another property is that, if we have  $d + 1$  sites  $s'_0, \dots, s'_d$  that lay on the surface of a  $(d - 1)$ -sphere<sup>5</sup> that does not have any other site on the interior, then the center point of the  $(d - 1)$ -sphere is the vertex shared only between the  $d + 1$  cells  $V(s'_0), \dots, V(s'_d)$  [8]. This is not true for less than  $d + 1$  sites on a  $(d - 1)$ -sphere because they are not enough to define it univocally, but is possible to have  $n > d + 1$  sites on a  $(d - 1)$ -sphere. In that case, the center of the  $(d - 1)$ -sphere is the shared vertex of the cells corresponding to the  $n$  sites. This is important to reason about the

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<sup>5</sup> A circumference in 2-dimensional space, a sphere in 3-dimensional space, an hypersphere in  $n$ -dimensional space with  $n \geq 3$ .

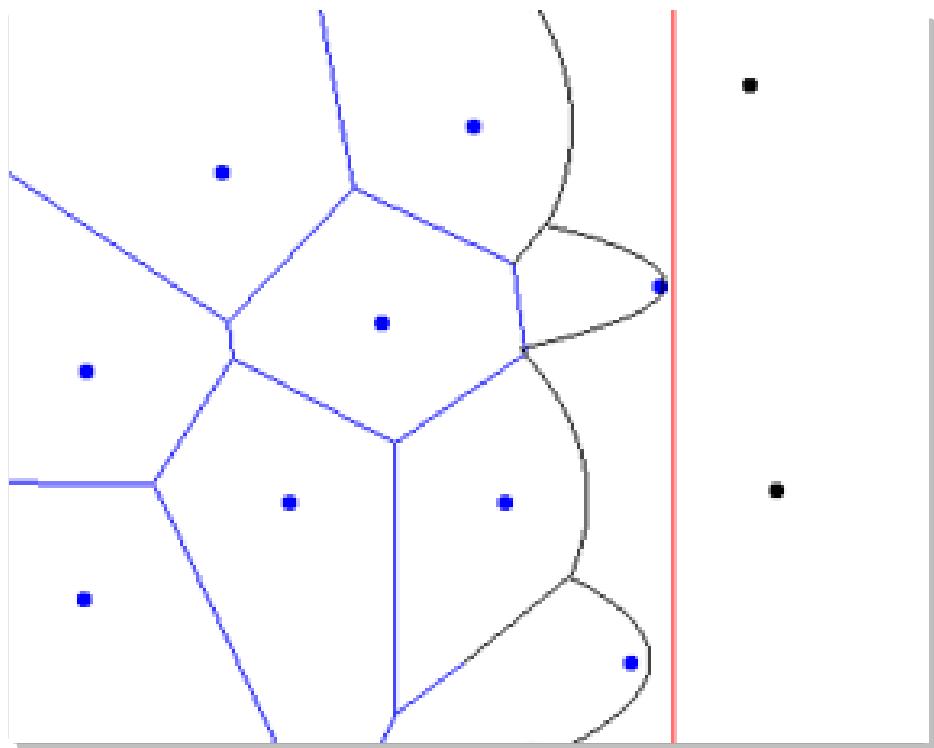


Figure 3.: Fortune's algorithm execution

topography of  $G(Vor(S))$  because if we allow more than  $d + 1$  sites on a  $(d - 1)$ -sphere then the maximum degree  $\Delta(G(Vor(S)))$  of the graph can be arbitrarily big (up to the number of vertices). However, the fact that we work with coordinates in  $\mathbb{E}^d$  legitimizes the restriction<sup>6</sup> of not allowing more than  $d + 1$  sites on an  $(d - 1)$ -sphere, limiting  $\Delta(G(Vor(S)))$  to  $d + 1$ .

### 3.4 STATISTICAL METHODS

In this section we briefly introduce the Monte Carlo Method (MCM) [29][36][3] and the Simulated Annealing (SA) [23][19], two statistical methods to calculate unknown quantities and to find functions minima. Additionally, we introduce Lagrangian Relaxation (LR) [39], a method to transform a constrained optimization problem in an unconstrained one by increasing the state space dimension.

#### 3.4.1 Notes on probabilities

##### 3.4.1.1 PE

For a random variable  $X$  normally distributed with

- mean  $\mu$ ;
- variance  $\sigma^2$ ;

for

$$r = 0.6745\sigma$$

we have that

$$\mathbf{P}(|X - \mu| < r) = \mathbf{P}(|X - \mu| > r) = 0.5.$$

Thus values of  $X$  that deviate from  $\mu$  less or more than  $r$  have the same probability, and  $r$  identifies the most PE in a normal distribution.

---

<sup>6</sup> We can also relax this restriction and in case create multiple nodes connected by zero-distance edges on the graph.

### 3.4.1.2 Probability central limit theorem (PCLT)

Consider  $N$  independent and *identically-distributed* random variables  $X_1, X_2, \dots, X_N$ , with same mean and same variance

$$\begin{aligned} E[X_1] &= E[X_2] = \dots = E[X_N] = m \\ \text{Var}(X_1) &= \text{Var}(X_2) = \dots = \text{Var}(X_N) = b^2. \end{aligned}$$

Consider the sum of those random variables:

$$Y = X_1 + X_2 + \dots + X_N;$$

we have that

$$\begin{aligned} E[Y] &= E[X_1 + X_2 + \dots + X_N] = Nm \\ \text{Var}(Y) &= \text{Var}(X_1 + X_2 + \dots + X_N) = Nb^2. \end{aligned}$$

Consider a normally distributed random variable  $Z$  with parameters:

$$\begin{aligned} \mu &= Nm \\ \sigma &= b\sqrt{N} \end{aligned}$$

with Probability Density Function (PDF)  $p_Z(x)$ .

The PCLT affirms that, for  $N$  big enough, and for every interval  $(x_1, x_2)$ , applies:

$$P(x_1 < Y < x_2) \approx \int_{x_1}^{x_2} p_Z(x) dx. \quad (10)$$

Thus, the sum of an elevate number of identically-distributed random variables is a random variable with normal distribution with mean  $Nm$  and variance  $Nb^2$ , even if  $X_1, X_2, \dots, X_N$  aren't normally distributed.

### 3.4.2 Monte Carlo Method (MCM)

If we suppose to calculate an unknown quantity  $m$ , we need to find a random variable  $X$  such that:

$$E[X] = m.$$

If we have such distribution with variance:

$$\text{Var}(X) = b^2$$

it is possible to formalize the following passages.

Consider  $N$  random variables  $X_1, X_2, \dots, X_N$  that have distribution identical to the distribution of  $X$ . For the PCLT Eq. (10) we have that, for  $N$  big enough

$$Y = X_1 + X_2 + \dots + X_N$$

is normally distributed with parameters

$$\begin{aligned}\mu &= Nm \\ \sigma &= b\sqrt{N}.\end{aligned}$$

For the *three sigma rule* [32] we have that:

$$P(\mu - 3\sigma < Y < \mu + 3\sigma) \approx 0.997$$

that is

$$P(Nm - 3b\sqrt{N} < Y < Nm + 3b\sqrt{N}) \approx 0.997$$

dividing by  $N$

$$P\left(m - \frac{3b}{\sqrt{N}} < \frac{Y}{N} < m + \frac{3b}{\sqrt{N}}\right) \approx 0.997$$

that is

$$P\left(\left|\frac{Y}{N} - m\right| < \frac{3b}{\sqrt{N}}\right) \approx 0.997$$

results in

$$P\left(\left|\frac{1}{N} \sum_{i=1}^N X_i - m\right| < \frac{3b}{\sqrt{N}}\right) \approx 0.997. \quad (11)$$

Equation (11) asserts that, if we extract a sample for each random variable  $X_i$ , the arithmetic mean of those values is approximately equal to  $m$ . Moreover, the error of such approximation is equal to  $3b/\sqrt{N}$ , that tend to 0 increasing  $N$ . It is also possible to further reduce the uncertainty ( $1 - 0.997 = 0.003$ ) by increasing the number  $k$  of sigma used for the approximation and evaluating the error  $kb/\sqrt{N}$ .

In practice, since the random variables  $X_i$  have the same distribution of  $X$ , it is sufficient to extract  $N$  samples from  $X$  to reach the same conclusions.

The Monte Carlo Method (MCM) is constituted by the following procedure, to be adapted according to the problems:

1. find the distribution  $X$  having desired quantity  $m$  as mean value and  $b^2$  as variance;
2. extract  $N$  samples from  $X$ , with  $N$  big enough to have an error as small as desired;
3. the arithmetic mean of those  $N$  samples is the approximation of the desired value  $m$ .

Essentially, we transforme the problem from *calculating m* to *finding the distribution X*, or anyway the  $N$  samples distributed accordingly to  $X$ .

If we want to characterize more in detail the error committed taking  $N$  samples, we can use to PE. If we set  $k = 0.6745$  then we have that

$$P\left(\left|\frac{1}{N} \sum_{i=1}^N X_i - m\right| < \frac{0.6745 \cdot b}{\sqrt{N}}\right) \approx 0.5$$

and so

$$r_N = \frac{0.6745 \cdot b}{\sqrt{N}}$$

indicates how much the value  $\frac{1}{N} \sum_{i=1}^N X_i$  deviates from the desired value  $m$ . Such value characterize the absolute error

$$\left| \frac{1}{N} \sum_{i=1}^N X_i - m \right|$$

committed taking  $N$  samples.

MCM is useful to simulate events that have an high degree of uncertainty in the inputs or an high degree of liberty in the state: for instance, numerically integrate a function with many dimensions or Simulated Annealing (SA) (Section 3.4.3).

### 3.4.3 Simulated Annealing (SA)

The SA is a method used to find the global maximum or minimum of a function. It is inspired by a method used in metallurgy that consists in heating and then cooling slowly a material to increase the size of the crystals and improving the chemico-physical properties. The function that must be optimized can be defined in a multiple-dimensional space.

### 3.4.3.1 Statistical thermodynamic

To describe the basic principles of statistical thermodynamic we consider the following example. In a one-dimensional lattice every point is a particle with a value of spin that can be *up* or *down*. If the lattice has  $N$  points then the system can be in  $2^N$  different configurations, where each one of those configurations corresponds to a value of energy, for instance:

$$E = B(n_+ - n_-)$$

where  $B$  is some constant,  $n_+$  is the number of particles with spin *up* and  $n_-$  is the number of particles with spin *down*.

The probability  $P(\sigma)$  of finding the system in a certain configuration  $\sigma$  is given by the distribution of *Boltzmann-Gibbs*:

$$P(\sigma) = C e^{-E_\sigma/T} \quad (12)$$

where  $E_\sigma$  is the energy of the configuration,  $T$  is the temperature<sup>7</sup> and  $C$  is a normalization constant.

The average energy of the system is then:

$$\begin{aligned} \bar{E} &= \frac{\sum_\sigma E_\sigma P(\sigma)}{\sum_\sigma P(\sigma)} \\ &= \frac{\sum_\sigma E_\sigma e^{-E_\sigma/T}}{\sum_\sigma e^{-E_\sigma/T}}. \end{aligned}$$

The computation of the value of  $\bar{E}$  can be difficult with an high number of states, but it is possible to create a MCM simulating the random fluctuation between the states such that the distribution given by Eq. (12) is respected. Starting from an arbitrary initial configuration, after a certain number of *Monte Carlo trials*, the method converges to the equilibrium status  $\bar{E}$  and it continues to fluctuate around it. SA is a method of this kind.

### 3.4.3.2 Simulated Annealing (SA) algorithm

SA operates on a system starting from a certain initial state  $s_0$ , then it executes a series of iterations where a neighbour of the state is evaluated and, with a certain distribution of probability, the system is moved in the new state or not.

---

<sup>7</sup> The real Boltzmann-Gibbs distribution is  $P(\sigma) = C e^{-E_\sigma/kT}$  where  $k$  is the *Boltzmann constant* and  $T$  is the thermodynamic temperature, but for the example the temperature is a parameter not correlated to the physical world, thus it is possible to ignore  $k$ .

A possible algorithm for a SA method is Algorithm 1.  $s_0$  is the initial state;  $\text{temp}$  is the function that assigns a temperature based on the current iteration number such that for low  $k$  the returned temperature is high and for high  $k$  the returned temperature is low;  $\text{neighbour}$  is the function that returns a random neighbour of the current state;  $\text{uniform}$  returns an uniformly-randomly chosen number in  $[0, 1]$ ;  $P_a$  is the distribution of accepting probability that depends on the energy of the current state, on the energy of the neighbour, and on the current temperature. In case of acceptance, the neighbour becomes the current state and the process continues.

---

**Algorithm 1** Simulated Annealing (SA)

---

```

1: function ANNEAL( $s_0$ )
2:    $s \leftarrow s_0$ 
3:   for  $k \leftarrow 0, k_{\text{Max}}$  do
4:      $T \leftarrow \text{temp}\left(\frac{k}{k_{\text{Max}}}\right)$ 
5:      $s_{\text{New}} \leftarrow \text{neighbour}(s)$ 
6:     if  $\text{uniform}(0, 1) < P_a(E(s), E(s_{\text{New}}), T)$  then
7:        $s \leftarrow s_{\text{New}}$ 
8:     end if
9:   end for
10:  return  $s$ 
11: end function

```

---

The relation with the statistical thermodynamic is that  $P_a$  is chosen such that Eq. (12) holds<sup>8</sup>, moreover  $\text{temp}$  returns decreasing values of temperature with the succession of iterations. This explains the comparison with the metallurgy annealing.

Initially  $P_a$  was chosen such that

$$P_a(E(s), E(s_{\text{New}}), T) = \begin{cases} 1, & \text{if } E(s_{\text{New}}) < E(s) \\ e^{-(E(s_{\text{New}}) - E(s))/T}, & \text{otherwise} \end{cases}$$

but this isn't strictly necessary to develop a SA method.

---

<sup>8</sup> A similar distribution is enough.

### 3.4.4 Lagrangian Relaxation (LR)

A general constrained discrete optimization problem can be expressed in the form:

$$\begin{aligned} & \underset{x}{\text{minimize}} && f(x) \\ & \text{subject to} && g(x) = 0 \end{aligned} \tag{13}$$

where  $x \in X$  is the state of the system in a discrete space  $X$ ,  $f(x)$  is the function to minimize, and  $g(x) = 0$  is the constraint. The functions can also be in a multidimensional discrete space, in that case the  $x$  is a vector  $x = (x_1, \dots, x_n)$  of variables.

To solve this class of problems a *Lagrange relaxation* method can be used [4]: it expands the variable space  $X$  by a *Lagrange multiplier* space  $\Lambda$ , equal in dimension to the number of constraints - one in the Problem 13.

The *generalized discrete Lagrangian function*, corresponding to the Problem 13, is:

$$L_d(x, \lambda) = f(x) + \lambda H(g(x)) \tag{14}$$

where  $\lambda$  is a variable in  $\Lambda$ ; if the dimension of  $\Lambda$  is more than one  $\lambda$ , it must be transposed in Eq. (14).  $H(x)$  is a non negative function with the property that  $H(0) = 0$  and aimed to transform  $g$  in a non negative function. For instance, it can be  $H(g(x)) = |g(x)|$  or  $H(g(x)) = g^2(x)$ .

Under the previous assumptions, the set of *local minima* in Problem 13 - that respect the constraints - coincides with the set of *discrete saddle point* in the augmented space. A point  $(x^*, \lambda^*)$  is a discrete saddle point if:

$$L_d(x^*, \lambda) \leq L_d(x^*, \lambda^*) \leq L_d(x, \lambda^*)$$

for all  $x \in N(x^*)$  and for all  $\lambda \in \Lambda$ , where  $N(x^*)$  is the set of all  $x^*$ 's neighbours.

To solve the optimization Problem 13 it is necessary to calculate, among the saddle points, the global minimum for  $f$ . We can use an optimization method, like SA, that descends in  $X$  and ascends in  $\Lambda$ .

## 3.5 INTERSECTIONS IN SPACE

We work in a spatial environment with polyhedral obstacles. Thus, in order to define admissible paths, first of all we need routines performing the following three basic geometric tasks:

1. establish if a point is in or out of a convex polyhedron;
2. check if a segment intersects a triangle;
3. establish whether two triangles intersect.

In the project we need to consider three kinds of collision detection methods in 3-dimension euclidean space.

### 3.5.1 Point inside convex polyhedron in 3D space

To test if a point  $p$  is inside a convex polyhedron  $V$  with vertices  $v_1, v_2, \dots, v_n$ , we use a method that rely on convex hulls [8][35].

---

#### Algorithm 2 Check if point $p$ is inside convex polyhedron $V$

---

```

1: function ISPOINTINPOLYHEDRON( $p, V$ )
2:    $inside \leftarrow True$ 
3:    $C \leftarrow \text{convexHullVertices}([p, v_1, v_2, \dots, v_n])$ 
4:   for all  $c \in C$  do
5:     if  $c = p$  then
6:        $inside \leftarrow False$ 
7:       break
8:     end if
9:   end for
10:  return  $inside$ 
11: end function

```

---

Algorithm 2 performs the first task. It first computes the vertices of the convex hull of all the vertices of  $V$  plus the point  $p$  and then checks if  $p$  is one of them or not. If  $p$  is on the convex hull that means that  $p$  is external<sup>9</sup> to  $V$  because we have extended the convex hull formed by the vertices of  $V$ . Otherwise this means that  $p$  is inside  $V$ .

The cost of this algorithm is

$$\mathcal{O}(n \log n)$$

where  $n$  is the number of vertices of  $V$ , because the cost to construct the convex hull is [8]  $\mathcal{O}(n \log n)$ , and then we have another negligible term  $\mathcal{O}(n)$  for the cycle on Line 4.

---

<sup>9</sup> Or  $p$  coincides with a vertex of  $V$ .

### 3.5.2 Segment-triangle in 3D space

We need to deal with the intersection between a segment  $S = \overline{\mathbf{a}_2\mathbf{b}_2}$  and a triangle  $T = \triangle \mathbf{a}_1\mathbf{b}_1\mathbf{c}_1$ .  $S$  and  $T$  can be in one of the following cases also summarized in Table 1:

- case 1**  $S$  and  $T$  do not intersect and the plane containing  $T$  is not in the sheaf of planes generated by the line containing  $S$ ;
- case 2**  $S$  and  $T$  do not intersect and the plane containing  $T$  is in the sheaf of planes generated by the line containing  $S$ ;
- case 3**  $S$  and  $T$  intersect only at one point and the plane containing  $T$  is not in the sheaf of planes generated by the line containing  $S$ ;
- case 4**  $S$  and  $T$  intersect in one or infinite points and the plane containing  $T$  is in the sheaf of planes generated by the line containing  $S$ .

The discriminating factors among the cases are two: the presence of intersection and coplanarity. Table 1.

	not coplanar	coplanar
not intersect	<b>case 1</b>	<b>case 2</b>
intersect	<b>case 3</b>	<b>case 4</b>

Table 1.: Relations between  $S$  and  $T$

In Fig. 4 a **case 3** situation is shown where there is intersection in only one point  $x$ . To establish whether  $S$  and  $T$  intersect, we need to solve four equations in four unknowns [35] where we look for a point  $x$  being a convex linear combination of  $\mathbf{a}_2$  and  $\mathbf{b}_2$  and at the same time a convex linear combination of  $\mathbf{a}_1$ ,  $\mathbf{b}_1$  and  $\mathbf{c}_1$ . In other words, when there is a collision, then there is a solution for the unknowns  $\alpha, \beta, \gamma, \delta, \zeta$  of the system

$$\begin{cases} \alpha\mathbf{a}_2 + \beta\mathbf{b}_2 = \gamma\mathbf{a}_1 + \delta\mathbf{b}_1 + \zeta\mathbf{c}_1 \\ \alpha + \beta = 1 \\ \gamma + \delta + \zeta = 1 \end{cases} \quad (15)$$

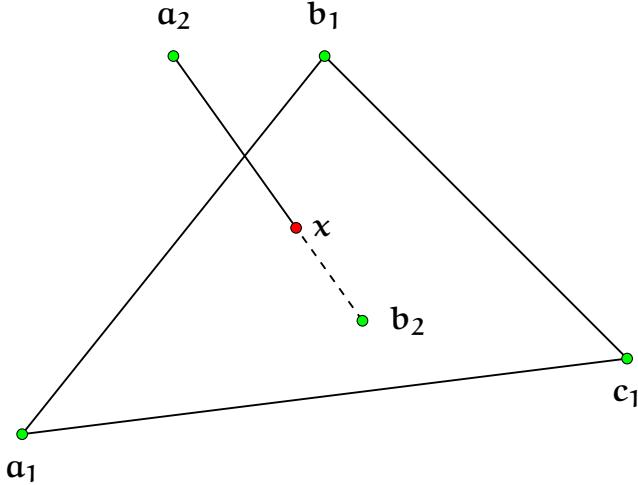


Figure 4.: Example intersection between a segment  $\overline{a_2b_2}$  and a triangle  $\triangle a_1b_1c_1$ .

with the further conditions

$$\left\{ \begin{array}{l} \alpha \geq 0 \\ \beta \geq 0 \\ \gamma \geq 0 \\ \delta \geq 0 \\ \zeta \geq 0. \end{array} \right. \quad (16)$$

Note that the first equation of System 15 has vectorial coefficients  $a_2$ ,  $b_2$ ,  $a_1$ ,  $b_1$ ,  $c_1$ , thus we have a system with five unknowns in five equations. If System 15 has just one solution then we are in **case 1** when System 16 is fulfilled or in **case 3** when it is not. If it has infinite solutions then we are on **case 2** or **case 4**, depending again on the fulfillment of System 16. Finally, if it has no solution, then S or T are degenerated.

We are interested in finding only **case 3** collisions because, for simplicity, we consider the special case of a segment that lays on the surface of

a triangle as nonintersecting with it, and, for coherence, we restrict the conditions of System 16 to

$$\begin{cases} \alpha > 0 \\ \beta > 0 \\ \gamma > 0 \\ \delta > 0 \\ \zeta > 0. \end{cases} \quad (17)$$

System 15 can be simplified in the three equations

$$\left\{ \begin{array}{l} \alpha \mathbf{a}_2 + (1 - \alpha) \mathbf{b}_2 = \gamma \mathbf{a}_1 + \delta \mathbf{b}_1 + (1 - (\gamma + \delta)) \mathbf{c}_1 \end{array} \right. \quad (18)$$

in the unknowns  $\alpha, \gamma$  and  $\delta$  with the relative conditions

$$\begin{cases} \alpha > 0 \\ \alpha < 1 \\ \gamma > 0 \\ \delta > 0 \\ \gamma + \delta < 1. \end{cases} \quad (19)$$

---

### Algorithm 3 Find intersection between segment S and triangle T

---

```

1: function INTERSECT(S, T)
2:   intersect ← False
3:   coordinates ← ∅
4:   if  $(\alpha, \gamma, \delta) \leftarrow \text{solve}(\text{System 18})$  then
5:     if satisfy(System 19) then
6:       intersect ← True
7:       coordinates ←  $(\gamma, \delta, 1 - (\gamma + \delta))$ 
8:     end if
9:   end if
10:  return (intersect, coordinates)
11: end function
```

---

Thus, Algorithm 3 which performs Task 2 essentially consists in solving System 18 with the parameters  $\mathbf{a}_2, \mathbf{b}_2, \mathbf{a}_1, \mathbf{b}_1$  and  $\mathbf{c}_1$  from S and T; and

then in checking if the solution is admissible. The condition of Line 4 is True if System 18 has solution and if that is unique.

We also have the positive secondary effect that from the solution  $(\alpha, \gamma, \delta)$  of System 18 we can extract the barycentric coordinates  $(\gamma, \delta, 1 - (\gamma + \delta))$  of the intersection point  $\mathbf{x}$  on the system of the vertices  $\mathbf{a}_1, \mathbf{b}_1, \mathbf{c}_1$  of  $T$ .

### 3.5.3 Triangle-triangle in 3D space

We are interested in detecting collisions between two triangles  $T_1 = \triangle \mathbf{a}_1 \mathbf{b}_1 \mathbf{c}_1$  and  $T_2 = \triangle \mathbf{a}_2 \mathbf{b}_2 \mathbf{c}_2$  in 3-dimensional space. First of all consider the coplanarity relation between the two triangles, we have the cases:

**case 1**  $T_1$  and  $T_2$  are contained by the same plane;

**case 2**  $T_1$  and  $T_2$  are contained by different planes.

To simplify the problem we decide - similarly to the case of intersection between segment and triangle - that when we are on **case 1** we consider  $T_1$  and  $T_2$  not intersecting in any case, even if from a geometrical point of view they share points. After this premise we can assert that the possible relation between  $T_1$  and  $T_2$  can be exclusively one of the following types [35]:

**type 0**  $T_1$  and  $T_2$  do not intersect;

**type 1** two edges of  $T_1$  intersect the plane section delimited by  $T_2$ , or vice versa;

**type 2** one edge of  $T_1$  intersects the plane section delimited by  $T_2$  and one edge of  $T_2$  intersects the plane section delimited by  $T_1$ .

On Fig. 5 and Fig. 6 we can see two examples of **type 1** and **type 2**, respectively. To establish if  $T_1$  and  $T_2$  intersect we need to check if every edge of  $T_1$  intersects  $T_2$  and if every edge of  $T_2$  intersects  $T_1$ . If we find at least one edge that intersects with one triangle, then  $T_1$  and  $T_2$  intersect. Algorithm 4 executes such check, the function intersect on Line 3 and Line 8 is the intersection check between a segment and a triangle done by Algorithm 3.

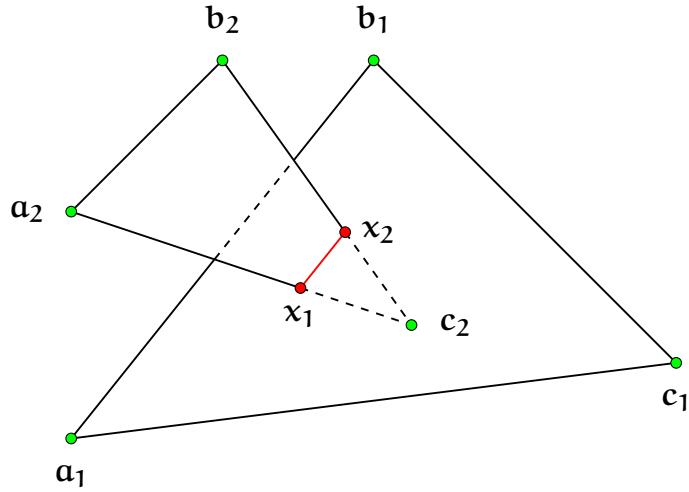


Figure 5.: Example of **type 1** intersection between a triangle  $T_1 = \triangle a_1 b_1 c_1$  and another triangle  $T_2 = \triangle a_2 b_2 c_2$ .

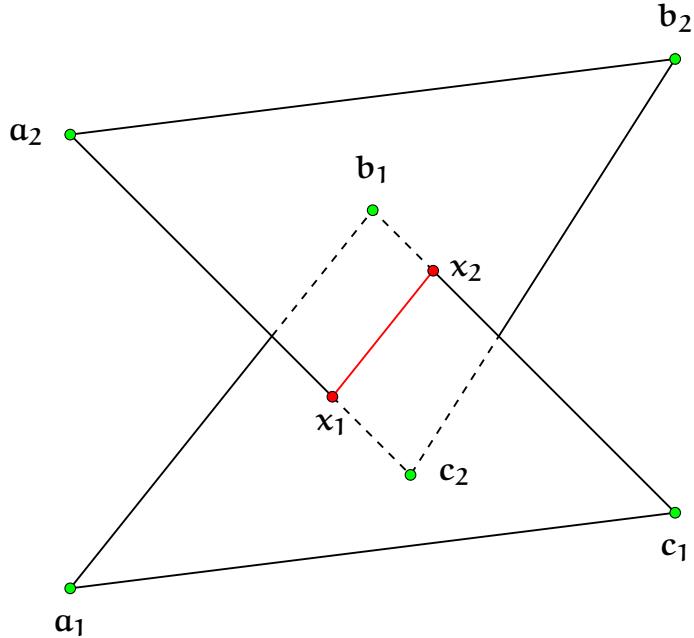


Figure 6.: Example of **type 2** intersection between a triangle  $T_1 = \triangle a_1 b_1 c_1$  and another triangle  $T_2 = \triangle a_2 b_2 c_2$ .

---

**Algorithm 4** Find intersection between triangle  $T_1$  and triangle  $T_2$ 

---

```
1: function INTERSECT( $T_1 = (\mathbf{a}_1, \mathbf{b}_1, \mathbf{c}_1)$ ,  $T_2 = (\mathbf{a}_2, \mathbf{b}_2, \mathbf{c}_2)$ )
2:   for all  $S \in \{\overline{\mathbf{a}_1\mathbf{b}_1}, \overline{\mathbf{b}_1\mathbf{c}_1}, \overline{\mathbf{c}_1\mathbf{a}_1}\}$  do
3:     if intersect( $S, T_2$ ) then
4:       return True
5:     end if
6:   end for
7:   for all  $S \in \{\overline{\mathbf{a}_2\mathbf{b}_2}, \overline{\mathbf{b}_2\mathbf{c}_2}, \overline{\mathbf{c}_2\mathbf{a}_2}\}$  do
8:     if intersect( $S, T_1$ ) then
9:       return True
10:    end if
11:   end for
12:   return False
13: end function
```

---



# 4

---

## SCENE REPRESENTATION

---

The problem of scene description basically consists in fixing a representation of the obstacles and of the path, besides establishing the structures adopted for their storage.

### 4.1 BASIC ELEMENTS AND PATH

First of all, since we are interested in spatial path planning, all the point coordinates are in  $\mathbb{E}^3$ . Furthermore, we concentrate on B-splines because we want a standard representation for the output of the algorithm, the path between a start point  $s$  and an end point  $e$ . B-spline curves are the standard adopted in CAD and CAGD systems [21][22].

The structures that uniquely identify a B-spline curve are three: its degree  $m$ , the associated control polygon and the extended knot vector.

Regarding the degree of the curve, we let the users choose among quadratics ( $m = 2$ ), cubics ( $m = 3$ ) and quartics ( $m = 4$ ). The users choose also the starting and ending points,  $s$  and  $e$  respectively, associated to the parameter values  $t_0 = \dots = t_m$  and  $t_{n+1} = \dots = t_{n+m+1}$ .

The number of vertices and the other vertices themselves come from the algorithm, and they depend on the position of  $s$  and  $e$  and on the obstacles, see Section 5.1 for details.

The knots are generated automatically using one of the two methods described in Section 5.4.

Thus, for the curve we memorize only the control vertices  $P$  and the degree  $m$ . As usual, in any computer graphic system, when we want its plotting, we tabulate  $S$  for a certain number<sup>1</sup> of values of  $t$  and then we draw the polygonal chain that connects them.

---

<sup>1</sup> Enough for having a smooth look.

## 4.2 BASIC OBSTACLE REPRESENTATION

Besides the curve, in the scene we need to represent the obstacles. We call Obs the set of all obstacles in scene. We choose to represent each obstacle  $Ob \in Obs$  as a set of triangular faces called Obstacle Triangular Faces (OTFs), each one containing three vertices. To summarize, we have

$$\begin{aligned} Obs &= \{Ob_0, \dots, Ob_{\#Obs}\} \\ Ob_i &= \{Otf_{i,0}, \dots, Otf_{i,\#Otf_i}\} & i = 0, \dots, \#Obs \\ Otf_{i,j} &= \{p_{i,j,0}, p_{i,j,1}, p_{i,j,2}\} & i = 0, \dots, \#Obs; j = 0, \dots, \#Otf_i \end{aligned}$$

where  $\#Obs$  is the number of obstacles in the scene and  $\#Otf_i$  is the number of OTFs in obstacle  $Ob_i$ .

We choose this specific configuration because this way all the intersections that can occur are between triangle and triangle or triangle and segment and they can be easily calculated. This implies that, if an obstacle is a polyhedron more complex than just a tetrahedron, its faces must to be preliminarily triangulated.

We provide the methods explained in Section 4.3 to abstract the creation of OTFs.

Using this solution, we can potentially insert open polyhedrons<sup>2</sup> or intersecting shapes in the scene, as we do not have any restriction on the position of the points  $p_{i,j,k}$ .

## 4.3 COMPLEX OBSTACLES

In order to simplify the scene construction, we create four methods to easily build obstacles:

- one for tetrahedrons;
- one for parallelepipeds<sup>3</sup>;
- a more general one for convex hulls;
- a special method for a bucket-shaped obstacle that we use in the tests.

Algorithm 5 takes the four vertices of a tetrahedron and adds to Obs a new obstacle that have all the faces of the unique tetrahedron that can be built with the four points.

---

<sup>2</sup> For instance a tetrahedron without one face

<sup>3</sup> Aligned with the axis.

---

**Algorithm 5** Abstract construction of tetrahedron

---

```

1: procedure BUILDTETRAHEDRON(Obs, a, b, c, d)
2:   Obs  $\leftarrow$  Obs  $\cup$  { {a, b, c}, {a, b, d}, {b, c, d}, {c, a, d} }
3: end procedure

```

---



---

**Algorithm 6** Abstract construction of convex hull polyhedron

---

```

1: procedure BUILDCONVEXHULLPOLYHEDRON(Obs, p0, ..., pn)
2:   Ob  $\leftarrow$   $\emptyset$ 
3:   facets  $\leftarrow$  convexHull({p0, ..., pn})
4:   for all f  $\in$  facets do
5:     simplices  $\leftarrow$  triangularize(f)
6:     for all {s0, s1, s2}  $\in$  simplices do
7:       Ob  $\leftarrow$  Ob  $\cup$  {s0, s1, s2}
8:     end for
9:   end for
10:  Obs  $\leftarrow$  Obs  $\cup$  Ob
11: end procedure

```

---

Algorithm 6 is more complex, first we need to build the convex hull of the input points (see [8] and [31] for details on the convex hull algorithm), then we obtain a set of facets that have to be triangulated (see [8] and [31] for details on the triangularization algorithms). Finally we add each triangle as a new OTF of the obstacle.

#### 4.4 BOUNDING BOX

We also give to the user the possibility of adding a bounding box around the scene. It is built as an obstacle, using OTFs, in fact we provide a method that takes two points **a** and **b** and builds the parallelepiped having those points as extremes and with all the faces triangularized like in Fig. 7.

In regards to the intersections, the OTFs of the bounding box are considered exactly like the OTFs of the obstacles throughout the whole project. The only differences are that the bounding box is not visible when the scene is plotted and a point inside the bounding box is not considered to be inside the obstacle.

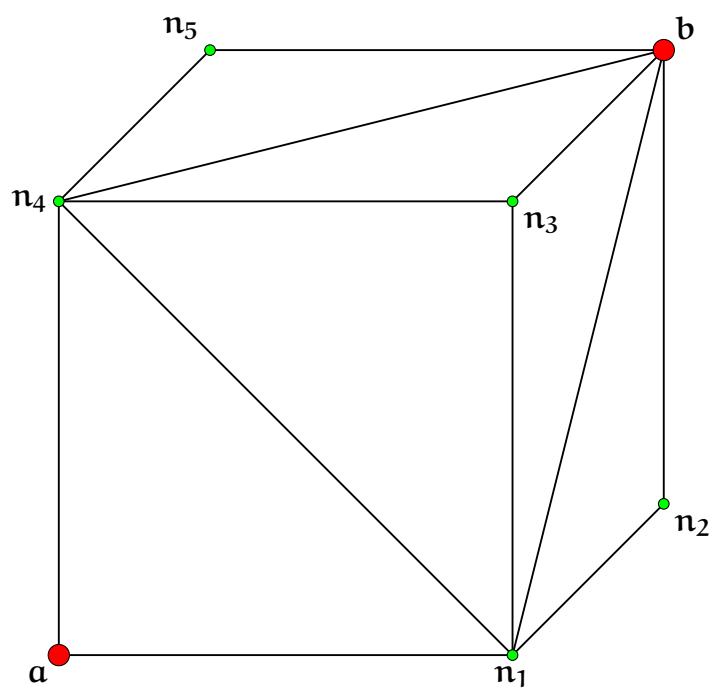


Figure 7.: Bounding box with extremes **a** and **b**.

# 5

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## ALGORITHMS

---

In this chapter we analyze step-by-step the algorithms that implement the different parts of the program. We do this with the help of the test scene in Fig. 8.

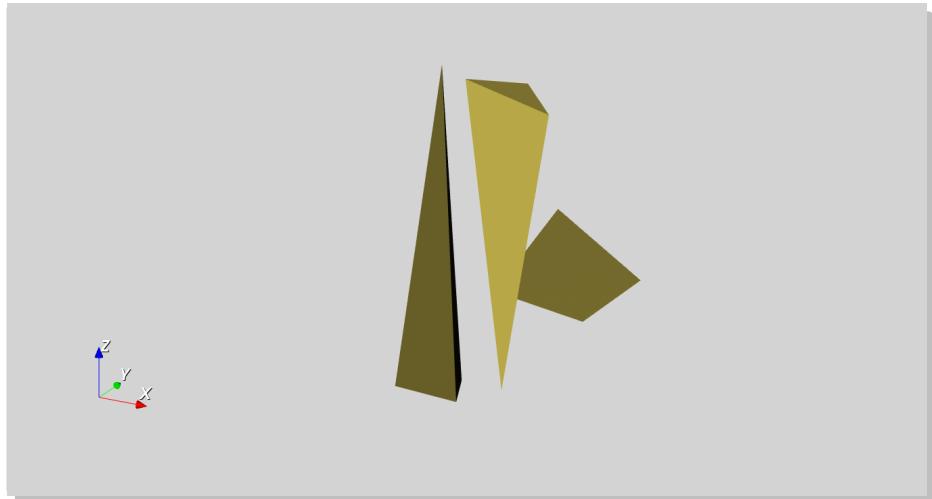


Figure 8.: Initial scene.

The general idea is to use an open B-spline curve of a certain degree interpolating the chosen starting and ending points, whose control polygon is a suitable modification of a polygonal chain extracted from a graph obtained with a VD method. In Section 5.1 we explain in detail how to build such polygonal chain. The chain, before being used as a control polygon for the B-spline, is refined and adjusted - as explained in detail in Section 5.2 and Section 5.3 - in order to ensure that the associated B-spline curve has no obstacle collision. Furthermore, in Section 5.4 we implement a method for an optional adaptive arrangement of the breakpoints of the B-spline. Finally, Section 5.5 is devoted to an optional post-processing of the path.

### 5.1 POLYGONAL CHAIN

In the first phase, the purpose is to extract a suitable polygonal chain from the scene, such that the extremes coincide with the start point  $s$  and the end point  $e$ . In particular, we are interested in short length chains. We calculate the shortest path in a graph that is obtained by using an adaptation to three dimensions of a well known bidimensional method [5][18][38] that use VDs as base.

We choose a Voronoi method because it builds a structure roughly equidistant from obstacles, resulting in a low probability of collisions between the curve and the obstacles.

#### 5.1.1 Base Graph

First we start distributing points on the OTFs and on an invisible bounding box, as in Fig. 9. The sites are distributed using a recursive method, for

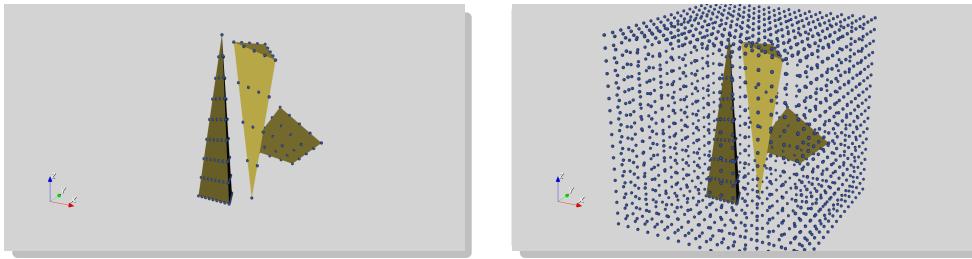


Figure 9.: Scene with Voronoi sites (distributed only on the obstacles surfaces on the left, and on obstacles and bounding box on the right).

each triangle of the scene we add three points - one for each vertex, if not already added before - and then we calculate the area of the triangle. If the area is bigger than a threshold, we decompose the triangle in four triangles adding three more vertices on the midpoints of the edges of the original triangle as in Fig. 10. We repeat the process recursively for each new triangle.

We construct the VD using the Fortune's algorithm [14] on those points as input sites, and we build a graph

$$G = (V, E)$$

using the vertices of the Voronoi cells as graph nodes in  $V$ , and the edges of the cells<sup>1</sup> as graph edges in  $E$ . Furthermore, we make  $G$  denser by

---

<sup>1</sup> Rejecting potential infinite edges.



Figure 10.: Decomposition of an OTF.

adding all the diagonals as edges for every cell's face, in other words we connect every vertex to every other vertex of a face.

Subsequently, we prune such graph deleting every edge that intersects an OTF using the methods explained in Section 3.5. The edge-pruning process considers a margin around the OTFs during the collision checks.

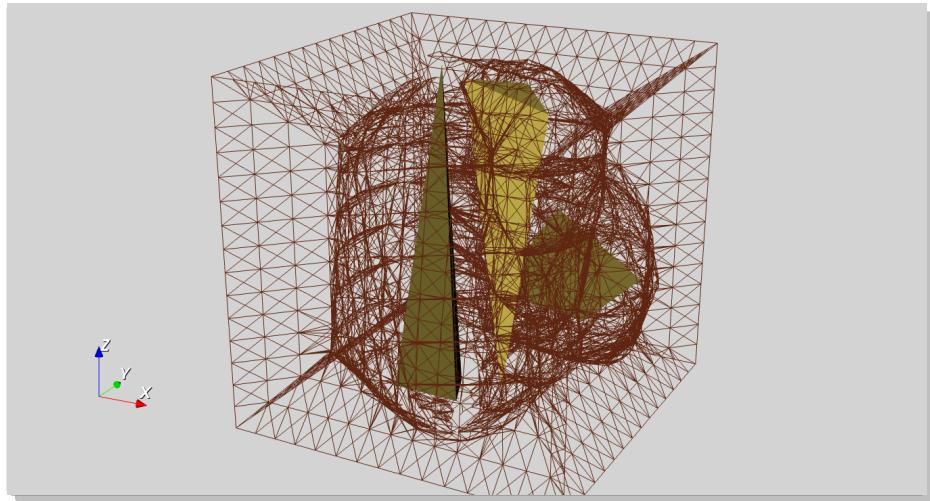


Figure 11.: Scene with pruned graph.

The result, visible in Fig. 11, is a graph that embraces the obstacles like a cobweb where the possible paths are roughly equidistant from the obstacles.

As visible in Fig. 12, in the bidimensional scenario the equivalent method implies distributing the sites (the blue dots) in the edges of the polygonal obstacles and then pruning the graph when an edge of the graph intersects an edge of the obstacle. The result is a sparse graph composed of chains around the obstacles (the green dots).

We decide to extend the method in 3 dimensions distributing points in the whole OTF surface. An alternative to this would be distributing points only along the edges of the obstacles.

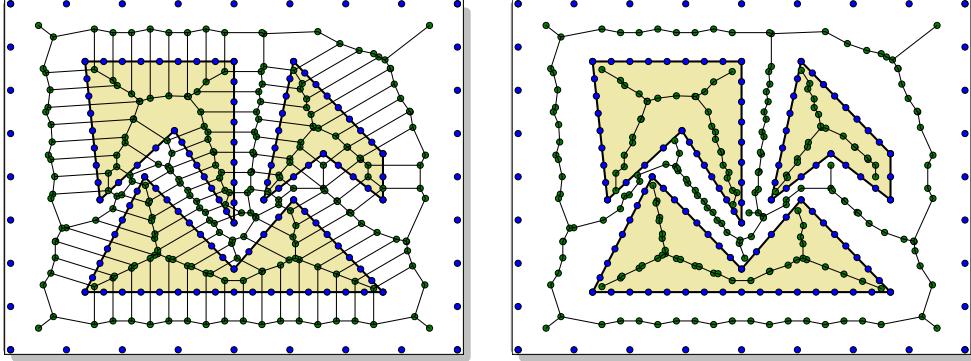


Figure 12.: Voronoi graph in 2D before (left) and after (right) pruning.

We attach the desired start and end points  $s$  and  $e$  on the obtained graph  $G$  and we can obtain a path between the two points using an algorithm like Dijkstra [10][24]. To attach  $s$  and  $e$  we design two alternative methods:

- the first method finds the vertex  $v_n \in V_{vis} \subseteq V$  such that  $dist(s, v_n) \leq dist(s, v_i), \forall v_i \in V_{vis}$ , where

$$V_{vis} = \{v \in V : \overline{sv_i} \text{ do not intersect any obstacle}\},$$

then adds  $s$  to  $V$  and the edge  $(s, v_n)$  to  $E$ ; similarly for  $e$ ;

- the second method adds  $s$  to  $V$  and all the edges  $(s, v_i) \forall v_i \in V_{vis}$ ; similarly for  $e$ .

Before using that path as a control polygon, we need to take into account the degree of the B-spline and the position of the obstacles, the details are in Section 5.2 and Section 5.3.

#### 5.1.1.1 Complexity considerations

Fortune's algorithm runs in time  $\mathcal{O}(|I| \log |I|)$  [8], where  $I$  is the set of input sites. If we impose a maximum area  $A$  for the obstacles <sup>2</sup> then  $|I| = \mathcal{O}(|O|)$  where  $O$  is the set of obstacles, because in the worst case we have that  $|I| = C \cdot A \cdot |O|$  for some constant  $C$  that depends on the chosen density of sites per area.

In conclusion, the time cost for the creation of the graph is

$$\mathcal{O}(|O| \log |O|) \tag{20}$$

---

<sup>2</sup> Inserting the obstacles in a progressive order, the area of the  $i$ -th obstacle cannot be a function  $f(i)$  of the number of the obstacles.

and the number of the vertices in the graph is

$$|V| = \mathcal{O}(|I|) = \mathcal{O}(|O|) \quad (21)$$

because the number of vertices in the resulting graph has the same order of magnitude of the number of input sites.

If we formulate the hypothesis of having maximum degree  $k$  in  $G$  - i.e. each vertex in  $V$  is connected to other  $k$  vertices at most - then we have that

$$|E| = \mathcal{O}(k|V|) = \mathcal{O}(k|O|). \quad (22)$$

In the worst case  $k = |V|$  and  $|E| = \mathcal{O}(|V|^2)$  but for VDs in plane there is a property that if we have  $n$  input sites that lay on a circumference, without any other site inside the circumference, then the center of the circumference is a vertex shared by  $n$  cells (Section 3.3 for details). The same property holds in the 3D case with respect to spheres. We can make the assumption that no more than three sites can lay on a circumference, hence, no vertex can have more than three neighbours, or the same with four vertices in sphere. This assumption is plausible because we use floating point numbers for the coordinates of the vertices of the obstacles, and it is unlikely that more than four points lay on a sphere. With this assumption  $k$  is a constant, and Eq. (22) becomes

$$|E| = \mathcal{O}(|V|) = \mathcal{O}(|O|).$$

To prune the graph of every edge that intersects obstacles, we need to solve a system of three unknowns in three equations for every edge and every OTF<sup>3</sup>, so we have a cost of

$$\mathcal{O}(|E| \cdot |O|) = \mathcal{O}(k|O|^2) \quad (23)$$

and, if we make the assumption of  $k$  constant, it becomes

$$\mathcal{O}(|O|^2).$$

### 5.1.2 Graph's transformation

Before calculating the shortest path on the chosen graph with Dijkstra [10][24], we transform it in a graph containing all the triples of three adjacent vertices in the original graph. This because we want to filter the

---

<sup>3</sup> See Section 3.5.2.

triples for collisions as described in Section 5.2.1. We call the transformed graph

$$G_t = (V_t, E_t)$$

where we have triples of vertices of  $G$  in  $V_t$ .

The original graph  $G$  is not directed and it is weighted with the distance from vertex to vertex, whereas the transformed graph  $G_t$  is directed and weighted. If in  $G$  the nodes  $a$  and  $b$  are neighbouring, and  $b$  and  $c$  are neighbouring, then  $G_t$  has the two nodes  $(a, b, c)$  and  $(c, b, a)$ . In  $G_t$  a node  $(a_1, b_1, c_1)$  is a predecessor of  $(a_2, b_2, c_2)$  if  $b_1 = a_2$  and  $c_1 = b_2$ , and the weight of the arc from  $(a_1, b_1, c_1)$  to  $(a_2, b_2, c_2)$  in  $G_t$  is equal to the weight of the arc from  $a_1$  to  $b_1 (= a_2)$  in  $G$ .

The steps necessary to create  $G_t$  are summarized in Algorithm 7. The input  $G$  is the base graph that has vertices  $V$  and edges  $E$ ,  $N_G(a)$  is the set of neighbours in  $G$  of the vertex  $a$ , and the output is  $G_t$ .

The transformation of the graph is useful only for the obstacle avoidance algorithm of Section 5.2.1, theoretically it is possible to bypass such transformation for the algorithm described in Section 5.2.2.

### 5.1.2.1 Complexity considerations

If we suppose a maximum degree  $k$  for each vertex in the graph  $G$  - i.e. each vertex in  $V$  can have  $k$  edges insisting on it at most, then the number of vertices in the transformed graph  $G_t$  is

$$|V_t| \leq |V| \cdot k \cdot (k-1) = \mathcal{O}(k^2|V|) \quad (24)$$

because for each vertex  $v$  in  $G$  we need to consider all the neighbours of  $v$  and the neighbours of the neighbours of  $v$  (excluded  $v$ ).

For how we define the triples neighbour rule in  $G_t$  we have that each triple is a predecessor of  $k-1$  other triples at most. For instance,  $(a, b, c)$  in  $V_t$  is the predecessor of all the triples  $(b, c, *)$  where  $*$  can be one of the  $k$  neighbours of  $c$  in  $V$  excluded  $b$ . Thus, the number of edges in  $G_t$  is

$$|E_t| \leq |V_t| \cdot (k-1) = \mathcal{O}(k|V_t|) = \mathcal{O}(k^3|V|). \quad (25)$$

Furthermore, the time cost for the creation of  $G_t$  is

$$\mathcal{O}(k^2|E|) = \mathcal{O}(k^3|O|) \quad (26)$$

because Algorithm 7 scans all the edges  $e$  on Line 3 for creating the transformed graph and for each iteration the biggest cost is due to the two *for* on Line 15 and Line 20.

---

**Algorithm 7** Create triples graph  $G_t$ 

---

```

1: function CREATETRIPLESGRAPH( $G$ )
2:    $V_t \leftarrow E_t \leftarrow \emptyset$ 
3:   for all  $(a, b) \in E$  do
4:      $leftOut \leftarrow leftIn \leftarrow rightOut \leftarrow rightIn \leftarrow \emptyset$ 
5:     for all  $v \in N_G(a) \setminus \{b\}$  do
6:        $leftOut \leftarrow leftOut \cup \{(v, a, b)\}$ 
7:        $leftIn \leftarrow leftIn \cup \{(b, a, v)\}$ 
8:        $V_t \leftarrow V_t \cup \{(v, a, b), (b, a, v)\}$ 
9:     end for
10:    for all  $v \in N_G(b) \setminus \{a\}$  do
11:       $rightOut \leftarrow rightOut \cup \{(v, b, a)\}$ 
12:       $rightIn \leftarrow rightIn \cup \{(a, b, v)\}$ 
13:       $V_t \leftarrow V_t \cup \{(v, b, a), (a, b, v)\}$ 
14:    end for
15:    for all  $o \in leftOut$  do
16:      for all  $i \in rightIn$  do
17:         $E_t \leftarrow E_t \cup (o, i)$ 
18:      end for
19:    end for
20:    for all  $o \in rightOut$  do
21:      for all  $i \in leftIn$  do
22:         $E_t \leftarrow E_t \cup (o, i)$ 
23:      end for
24:    end for
25:  end for
26:   $G_t \leftarrow (V_t, E_t)$ 
27:  return  $G_t$ 
28: end function

```

---

## 5.2 OBSTACLE AVOIDANCE

Before using the polynomial chain extracted as explained in Section 5.1 as a control polygon for the B-spline, we need to discuss a problem: every possible path in the graph  $G$  is free from collisions by construction - in fact we prune the graph of every edge that intersects an obstacle - but this does not guarantee that the associated curve will not cross any obstacle. This concept is exemplified in Fig. 13.

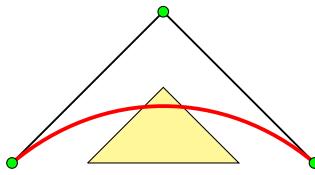


Figure 13.: B-spline that intersects an obstacle in the plane.

In this chapter we formulate the hypothesis of using quadratic B-splines<sup>4</sup>, in Section 5.3 we explain how it is possible to use curves with a higher degree. With this assumption, we can exploit the CHPs explained in Section 3.2 and assert that the resulting curve is contained inside the union of all the triangles of three consecutive control vertices of the control polygon. Using that property we can solve the problem of the collision, maintaining all the triangles associated to the control polygon free from collision with OTFs. Note that the CHP of quadratic B-splines is also valid in space, hence, the convex hull is still composed of triangles, like the faces of the obstacles. This simplifies all the checks for collisions because they are all between triangles in space and we can use the methods described in Section 3.5.

We design two different algorithms to approach the collision problem. The first solution, described in Section 5.2.1, implements a modified version of Dijkstra's algorithm that finds the shortest path from start to end in the graph such that all the triangles formed by three consecutive points in the path are free from collisions. The second solution, described in Section 5.2.2, uses the classical Dijkstra's algorithm to find the shortest path from  $s$  to  $e$  in the graph  $G$ , checking later for collisions in the triangles formed of three consecutive points in such path. When a collision is found we add vertices to the path to manage that.

---

<sup>4</sup> B-spline curves with degree 2.

### 5.2.1 First solution: Dijkstra's algorithm in $G_t$

The first solution of the problem exploits the graph  $G_t$  obtained as explained in Section 5.1.2. Before applying Dijkstra's algorithm to  $G_t$  all the triples are filtered checking if the triangle composed of the vertices of the triple intersects an OTF. If a triple intersects an obstacle then it is removed from the graph so that a path cannot pass from such vertices in that order.

Note that if a triple  $(a, b, c)$  is removed from  $V_t$  - and consequently also the triple  $(c, b, a)$  - this does not necessarily exclude the three vertices  $a, b, c$  from being part of the final polynomial chain. For instance, in Fig. 14 we have a graph  $G$  with vertices  $a, b, c, d, e, f$  and an obstacle that intersects triples on the transformed graph<sup>5</sup>  $G_t$ . The triple  $(a, b, c)$  and  $(c, b, a)$  are removed from  $G_t$  because the corresponding triangle intersects the obstacle, and the path  $d \rightarrow a \rightarrow b \rightarrow c \rightarrow e$  cannot be admissible. This doesn't preclude the nodes  $a, b$  and  $c$  to be part of the final admissible path  $d \rightarrow a \rightarrow b \rightarrow e \rightarrow c \rightarrow f$ .

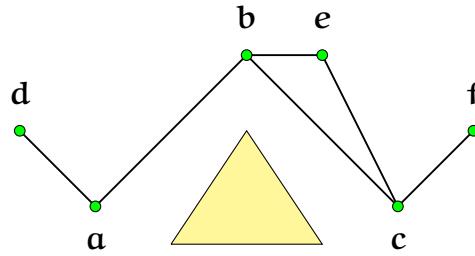


Figure 14.: Example of triples.

On the cleaned transformed graph it is possible to find the shortest path

$$P_t = (a_0, b_0, c_0), (a_1, b_1, c_1), \dots, (a_i, b_i, c_i), \dots, (a_n, b_n, c_n)$$

using an algorithm like Dijkstra. Then the shortest path  $P$  in  $G$  is constructed by taking the central vertex  $b_i$  of every triple  $(a_i, b_i, c_i)$  of  $P_t$ , plus the extremes  $a_0$  and  $c_n$  of the first and last triple, obtaining

$$P = a_0, b_0, b_1, \dots, b_i, \dots, b_{n-1}, b_n, c_n.$$

---

<sup>5</sup> In the plane, this graph cannot be obtained using the procedure based on VDs explained in Section 3.3, but a similar situation is plausible considering Voronoi cells in space.

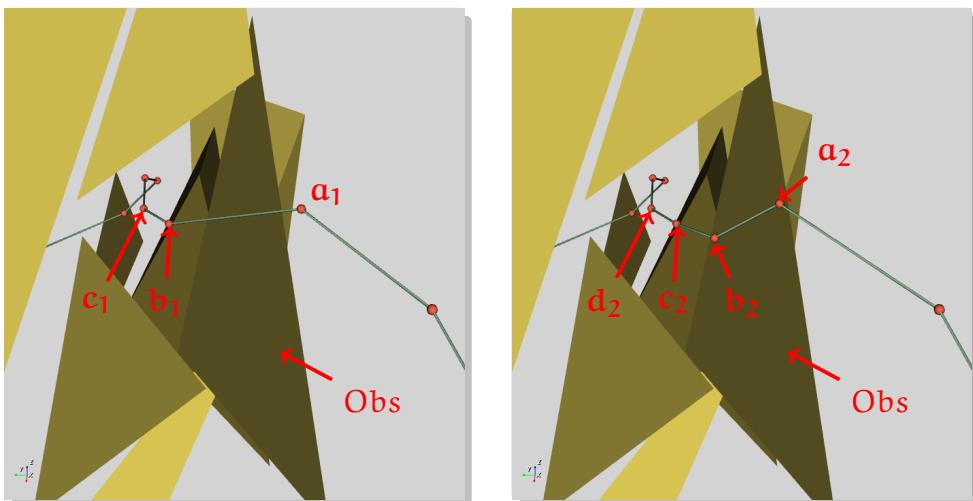


Figure 15.: Effects of application of solution one.

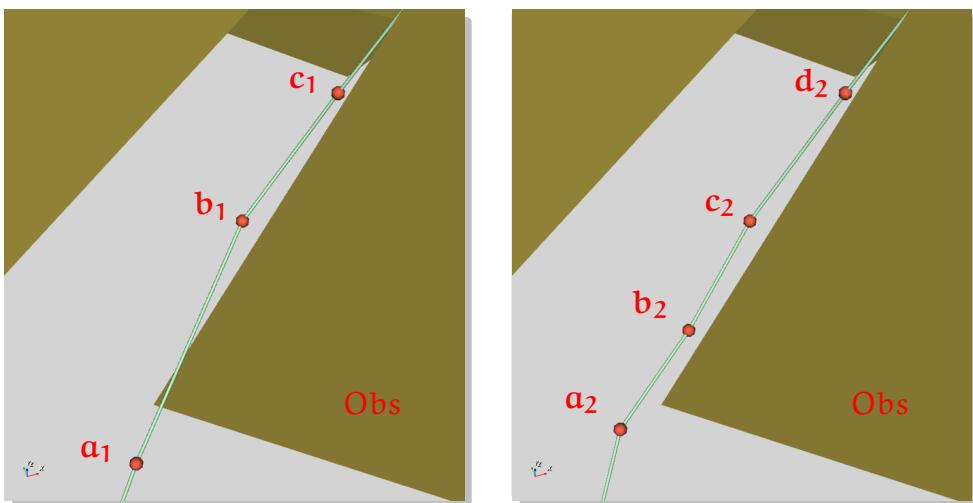


Figure 16.: Effects of application of solution one, other viewpoint.

In Fig. 15 and Fig. 16 the effect of the application of the first solution is shown. The triangle formed by the vertices  $a_1, b_1, c_1$  in the left picture of Fig. 15 is colliding with the obstacle Obs in the back. In the right picture there is the path  $a_2, b_2, c_2, d_2$  obtained applying the solution - in this case no triangles in the path collide with obstacles. In Fig. 16 another point of view of pictures in Fig. 15 is visible.

### 5.2.1.1 Complexity considerations

For each triple and each OTF we need to solve three  $3 \times 3$  linear systems for the collision check<sup>6</sup>, hence, in total the cost is

$$\mathcal{O}(|V_t| \cdot |O|)$$

and for Eq. (21) and Eq. (24) this is equal to

$$\mathcal{O}(|O|^2 k^2). \quad (27)$$

The cost of applying Dijkstra's algorithm<sup>7</sup> in  $G_t$  is [1][26]

$$\begin{aligned} \mathcal{O}(|E_t| + |V_t| \log |V_t|) &= \mathcal{O}(k^3 |V| + k^2 |V| \log(k^2 |V|)) \\ &= \mathcal{O}(k^3 |O| + k^2 |O| \log(k^2 |O|)). \end{aligned} \quad (28)$$

Such cost has two special cases:

- if  $G$  is a *clique* - i.e. each node in  $V$  is connected to every other node [1] - then  $k = |V| - 1$  and the cost is

$$\mathcal{O}(|V|^4);$$

- if  $k$  is constant - i.e. doesn't grow with  $|V|$  - the cost is

$$\mathcal{O}(|V| \log |V|).$$

The latter case is the more plausible if we assume the hypothesis that no more than four input sites in space can be on the same sphere, in fact in that case every Voronoi cell cannot have a vertex with more than four edges connected to it (see Section 3.3 for details).

If we sum all the costs we obtain:

$$\mathcal{O}(k^2 |O|^2 + k^3 |O|) \quad (29)$$

---

<sup>6</sup> See Section 3.5.3.

<sup>7</sup> In the worst case where no triples are removed in the cleaning phase.

where all the other terms are absorbed in those two. If we have  $k$  constant, as we said before, then we have an overall cost of

$$\mathcal{O}(|O|^2) \quad (30)$$

that originates from the collision-check controls.

We can improve this result if we divide the algorithm in two parts:

1. first we can construct the graph with cost  $\mathcal{O}(|O|^2)$ ;
2. then we can use the same graph in different situations<sup>8</sup> with cost  $\mathcal{O}(|O| \log |O|)$ , only for the routing.

Description	Cost	Reference
Creation of $G$	$\mathcal{O}( O  \log  O )$	Eq. (20)
Pruning of $G$	$\mathcal{O}(k O ^2)$	Eq. (23)
Creation of $G_t$	$\mathcal{O}(k^3 O )$	Eq. (26)
Pruning of $G_t$	$\mathcal{O}( O ^2 k^2)$	Eq. (27)
Routing in $G_t$	$\mathcal{O}(k^3 O  + k^2 O  \log(k^2 O ))$	Eq. (28)
Total	$\mathcal{O}(k^2 O ^2 + k^3 O )$	Eq. (29)
Total ( $k$ constant)	$\mathcal{O}( O ^2)$	Eq. (30)

Table 2.: Summary of the costs for solution one

On Table 2 we summarize all the terms that contributes to the total costs, and the total cost itself.

### 5.2.2 Second solution: Dijkstra's algorithm in $G$

The First solution is interesting from an algorithmic point of view, but it is not very practical. It ignores all the triples that intersect an obstacle, thus possible paths in  $G$  are lost.

We develop a solution that uses another approach: obtain the shortest path from the Voronoï's graph  $G$  directly using Dijkstra's algorithm, without removing any triple. On this path - that we call  $P$  - we check every triple of consecutive vertices, and if it collides with an OTF then we take countermeasures (see Section 3.5.3 for the procedure implemented

---

<sup>8</sup> With specific starting and ending points.

to identify collisions between two triangles). For instance, if the path is composed from the vertices

$$P = (\mathbf{v}_0, \mathbf{v}_1, \dots, \mathbf{v}_n)$$

then we check every one of the triangles

$$\begin{aligned} T_0 &= \Delta v_0 v_1 v_2 \\ T_1 &= \Delta v_1 v_2 v_3 \\ &\dots \\ T_i &= \Delta v_i v_{i+1} v_{i+2} \\ &\dots \\ T_{n-3} &= \Delta v_{n-3} v_{n-2} v_{n-1} \\ T_{n-2} &= \Delta v_{n-2} v_{n-1} v_n \end{aligned}$$

for intersections with OTFs.  $\Delta v_i v_j v_k$  denotes the triangle having points  $v_i$ ,  $v_j$  and  $v_k$  as vertices.

Consider that  $G$  is pruned from all the edges that intersect any obstacle, thus none of the edges of the triangles  $T_i$  can intersect an OTF. The only possibility is that edges<sup>9</sup> of OTF intersect a triangle  $T_i$ . Hence for each  $T_i$  we have a (possibly empty) set of points of intersection between it and the edges of each OTF - we call that set  $O$ .

In Fig. 17 we have an example of the triangle

$$T_i = \Delta v_i v_{i+1} v_{i+2}$$

that is intersected by obstacles in the points

$$O = \{\mathbf{o}_1, \mathbf{o}_2, \mathbf{o}_3\}.$$

Each one of the points in  $O$  is expressed in barycentric coordinates of the vertices  $v_i$ ,  $v_{i+1}$  and  $v_{i+2}$  of the triangle:

$$\begin{aligned} \mathbf{o}_1 &= \alpha_1 v_i + \beta_1 v_{i+1} + \gamma_1 v_{i+2} \\ \mathbf{o}_2 &= \alpha_2 v_i + \beta_2 v_{i+1} + \gamma_2 v_{i+2} \\ \mathbf{o}_3 &= \alpha_3 v_i + \beta_3 v_{i+1} + \gamma_3 v_{i+2} \end{aligned}$$

where  $\alpha_i + \beta_i + \gamma_i = 1$  for  $i = 1, 2, 3$ .

We want to avoid collisions adding vertices in the control polygon, such that consecutive triangles are free from obstacles. We obtain this by adding two new control vertices:

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<sup>9</sup> If we ignore special cases, two edges for each OTF at most.

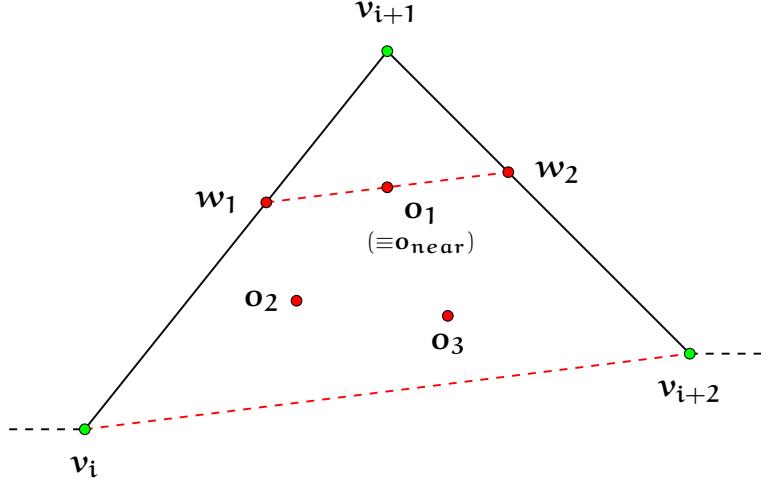


Figure 17.:  $T_i (= \triangle v_i v_{i+1} v_{i+2})$  and the points  $o_1, o_2, o_3$  of intersection between it and the edges of some OTFs.

- $w_1$  between  $v_i$  and  $v_{i+1}$ ;
- $w_2$  between  $v_{i+1}$  and  $v_{i+2}$ .

We add those points in a way that makes the segment  $\overline{w_1 w_2}$  parallel to the segment  $\overline{v_i v_{i+2}}$  and  $\overline{w_1 w_2}$  passing just above the obstacle point  $o_{near}$  that is the nearest to  $v_{i+1}$  ( $o_1$  in Fig. 17). The degenerate triangles  $\triangle v_i w_1 v_{i+1}$  and  $\triangle v_{i+1} w_2 v_{i+2}$ , and the not degenerate triangle  $\triangle w_1 v_{i+1} w_2$  replace the original triangle  $T_i$ . They are built in a way that do not make them collide with obstacles.

When we check for collisions between a segment and a triangle, we resolve a system of three unknowns in three equations and we extract the barycentric coordinates of the point of collision from the solutions. When we have all the coordinates of the points in O, we can obtain  $o_{near}$  by picking the one with the biggest  $\beta$  and then, using the corresponding  $\beta_{near}$ , we can obtain

$$\begin{aligned} W_1 &= \beta_{near} v_{i+1} + (1 - \beta_{near}) v_i \\ W_2 &= \beta_{near} v_{i+2} + (1 - \beta_{near}) v_{i+2}. \end{aligned}$$

In Fig. 18 and Fig. 19 we can see the effects of the application of this solution to a piece of the curve. The original pieces of control polygon are on the left pictures; the triangle composed of those vertices collide with the obstacle on the back. The two new vertices  $w_1$  and  $w_2$  are added to avoid the collision.

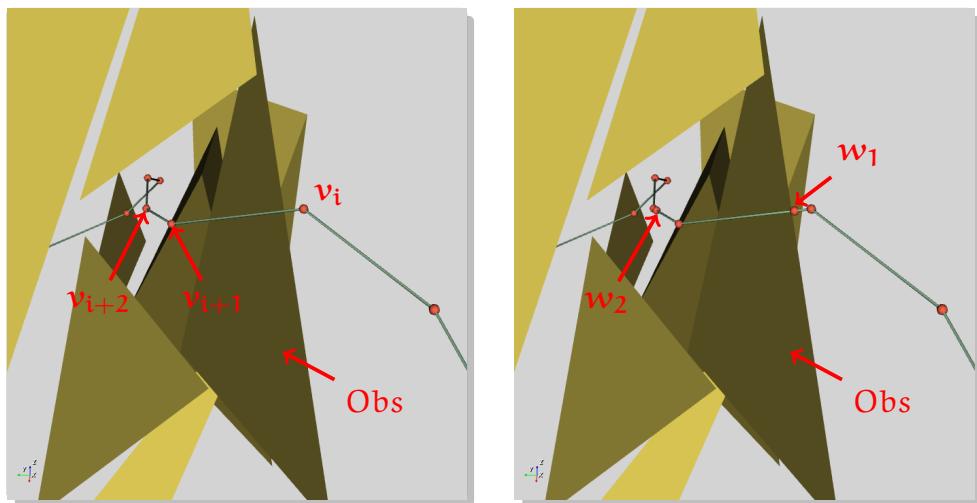


Figure 18.: Effects of application of solution two.

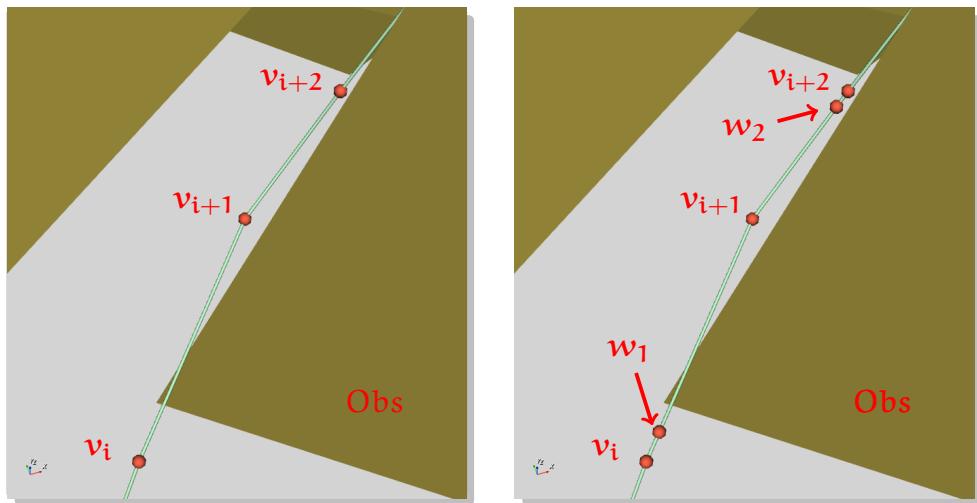


Figure 19.: Effects of application of solution two, other viewpoint.

### 5.2.2.1 Complexity considerations

For this solution we still have the costs of Eq. (20) and Eq. (23) for the creation and pruning of the graph  $G$ . In addition, we need to apply Dijkstra's algorithm in  $G$  to obtain  $P$  with a cost [1][26]

$$\mathcal{O}(|E| + |V| \log |V|).$$

For Eq. (21) and Eq. (22) this cost is equal to

$$\mathcal{O}(k|O| + |O| \log |O|) \quad (31)$$

and if we make the assumption of  $k$  constant we have a cost

$$\mathcal{O}(|O| \log |O|).$$

We need to consider every face of obstacles in  $O$  for every triangle in  $P$  to check and remove the collisions in the path. The cost to do this is<sup>10</sup>  $\mathcal{O}(|P| \cdot |O|)$  where  $|P|$  means the number of vertices in  $P$ . In the worst case  $|P| = \mathcal{O}(|V|) = \mathcal{O}(|O|)$ , hence we have a cost

$$\mathcal{O}(|P| \cdot |O|) = \mathcal{O}(|O|^2). \quad (32)$$

Summing up all the costs, we have

$$\mathcal{O}(k|O|^2) \quad (33)$$

and, if we consider  $k$  constant,

$$\mathcal{O}(|O|^2). \quad (34)$$

On Table 3 we summarize all the terms that contribute to the total cost, and the total cost itself.

The cost is comparable with the one of the first solution. Furthermore, in this case we can divide the algorithm in two parts:

1. first we can construct  $G$  with cost  $\mathcal{O}(|O|^2)$ ;
2. then we can use it for different situations with cost  $\mathcal{O}(|O| \log |O| + |P| \cdot |O|)$ .

---

<sup>10</sup> If #OTFs =  $\mathcal{O}(|O|)$  - i.e. the number of OTFs does not grow faster than the number of obstacles.

Description	Cost	Reference
Creation of G	$\mathcal{O}( O  \log  O )$	Eq. (20)
Pruning of G	$\mathcal{O}(k O ^2)$	Eq. (23)
Routing in G	$\mathcal{O}(k O  +  O  \log  O )$	Eq. (31)
Clean path	$\mathcal{O}( P  \cdot  O ) = \mathcal{O}( O ^2)$	Eq. (32)
Total	$\mathcal{O}(k O ^2)$	Eq. (33)
Total (k constant)	$\mathcal{O}( O ^2)$	Eq. (34)

Table 3.: Summary of the costs for solution two.

### 5.3 DEGREE INCREASE

We have hitherto assumed we are dealing only with quadratic B-splines - i.e. of degree 2 - because, for the CHP (Section 3.2.1), we need to check intersections only between two triangles (one belonging to P and the other to OTFs). If we want to use higher degree curves, we can modify the previous algorithms to deal with polyhedral convex hulls, but this implies an increase in complexity.

We are interested in increasing the degree to achieve smooth curves with continuous curvature and torsion. We adopt a compromise: we adapt the path obtained from the previous algorithms adding vertices and forcing the curve to remain in the same convex hull. However, this approach has the disadvantage that we cannot achieve a good torsion<sup>11</sup> because the curve changes plane in an inflection point of the curvature.

We modify

$$P = (v_0, \dots, v_n)$$

adding a certain number of aligned new vertices ( $w_0, w_1, \dots$ ) between each pair  $(v_i, v_{i+1})$  of vertices in  $P$  for  $i = 0, \dots, n - 1$ . The number of  $w_j$  between each pair  $(v_i, v_{i+1})$  depends on the desired grade of the curve. In fact we need  $m - 2$  new vertices between each  $(v_i, v_{i+1})$  for B-spline curves of degree  $m$ . Thus the final modified path for a B-spline curve of degree  $m \geq 3$  is

$$\tilde{P} = (v_0, w_0, \dots, w_{m-3}, v_1, \dots, v_i, w_{i(m-2)}, \dots, w_{(i+1)(m-2)-1}, v_{i+1}, \dots, v_n).$$

This strategy is used in this project only to lift the degree from 2 to 3 or 4.

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<sup>11</sup> We can improve this with the post process.

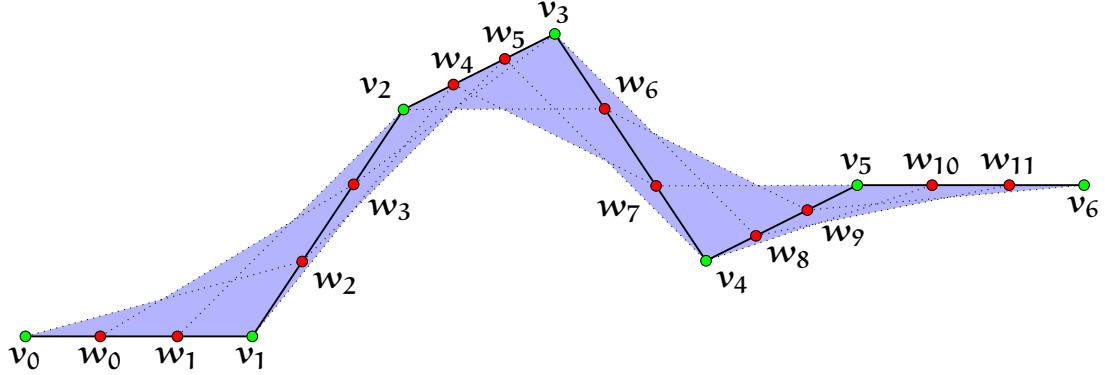


Figure 20.: Increase the degree  $m$  from 2 to 4.

An example of path

$$P = (v_0, v_1, v_2, v_3, v_4, v_5, v_6)$$

is visible in Fig. 20. We have the vertices of  $P$  in green, the added vertices in red and the cyan area is the convex hull of the final curve.

We want to adapt  $P$  to quartic B-spline curves, hence we need to add two new vertices between each pair of vertices  $(v_i, v_{i+1})$  for  $i = 0, \dots, 6$ . Those new vertices are

$$(w_0, w_1, w_2, w_3, w_4, w_5, w_6, w_7, w_8, w_9, w_{10}, w_{11}).$$

Note that, with this algorithm, when we increase the degree from 2 to  $m \geq 3$  we have that the convex hull containing a B-spline curve of degree  $m$  in  $\tilde{P}$  is a subset of the convex hull containing a B-spline curve of degree 2 in  $P$ . This happens because the polyhedrons of consecutive  $m+1$  vertices in  $\tilde{P}$  collapse in triangles contained inside the triangles of consecutive vertices in  $P$ . For instance, in Fig. 20 the convex hull of the first 5 vertices  $v_0, w_0, w_1, v_1, w_2$  of  $\tilde{P}$  coincides with the triangle  $\Delta v_0 v_1 w_2$  that is contained inside the triangle  $\Delta v_0 v_1 v_2$  of the first 3 vertices of  $P$ .

One effect of the application of this method is that a curve of degree  $m$  in  $\tilde{P}$  touches every segment of the original control polygon  $P$ . This is because adding  $m-2$  aligned vertices between each pair  $(v_i, v_{i+1})$  will result in  $m$  aligned vertices on each original segment (Section 3.2.2).

## 5.4 KNOTS SELECTION

In the previous sections we never discuss the criterion adopted to determine the extended knot vector  $T$

$$T = \{t_0, \dots, t_{m-1}, t_m, \dots, t_{n+1}, t_{n+2}, \dots, t_{n+m+1}\}$$

associated to the B-spline curve.

In this section we discuss two methods implemented to establish  $T$ .

First of all, we want the curve to interpolate the chosen start and end points that correspond to the extremes  $v_0$  and  $v_n$  of the extracted path  $P$ . We see in Section 3.2.4 that we can achieve such interpolation if we impose

$$\begin{aligned} t_0 &= t_1 = \dots = t_m = a \\ t_{n+1} &= t_{n+2} = \dots = t_{n+m+1} = b \end{aligned} \tag{35}$$

where  $a$  and  $b$  are the extremes of the parametric domain of the curve.

The constraint of Eq. (35) is a mandatory choice, thus we cannot change it. Regarding the parametric domain, we choose it to be  $[0, 1]$  because changing the extremes do not change the behavior of the curve, only changing the ratios of the distances between the knots is effective [12]. We still need to chose how to select the inner  $n - m$  knots  $t_{m+1}, \dots, t_n$ , and we develop two different ways to do this:

**method 1** Use a uniform partition where  $t_i - t_{i-1} = c$  for  $i = m + 1, \dots, n + 1$  for  $c$  constant;

**method 2** Use an adaptive partition, where we try to create dense knots in correspondence of points on the curve where we have dense control vertices.

**method 1** is the easiest way to choose a knot vector and it is a common first choice in textbooks [12][11], but it has the disadvantage of ignoring the geometry of the curve [12]. The steps to accomplish **method 1** are quite straightforward: we need to pick the nodes

$$\frac{i}{n - m + 1}$$

for  $i = 1, \dots, n - m$ . Thus, we concentrate on **method 2**.

We start from the idea that if we have a control polygon with uniformly-spaced vertices - i.e.  $\|v_1 - v_0\|_2 = \|v_2 - v_1\|_2 = \dots = \|v_n - v_{n-1}\|_2$  - then

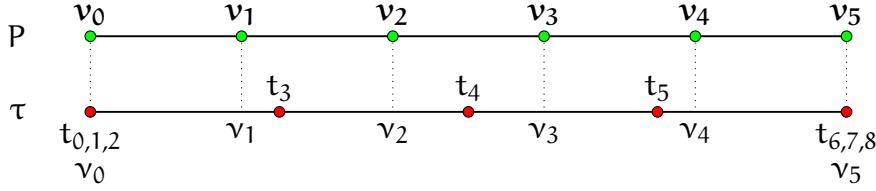


Figure 21.: Optimal case for a quadratic curve (we want uniform partition).

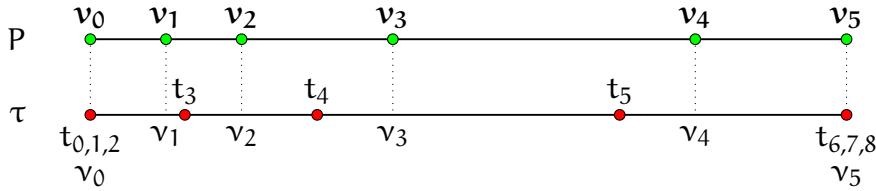


Figure 22.: General case for a quadratic (same distances between  $t_i$  and enclosing  $v_j, v_{j+1}$  as Fig. 21).

we agree on a uniform partition of the knots ( $t_{m+1} - t_m = t_{m+2} - t_{m+1} = \dots = t_{n+1} - t_n$ ). In Fig. 21 there is an example of a quadratic B-spline curve with uniformly-spaced control polygon. The above segment is a *rectified* visualization of the control polygon with six control vertices  $v_0, \dots, v_5$ . The segment below represents the partition of the domain from  $a$  (on the left) to  $b$  (on the right), with the projections  $v_0, \dots, v_5$  of the control vertices, scaled in length to the parametric domain axis<sup>12</sup>, and the knots  $t_0, \dots, t_8$  on it.

Starting from this situation, if we have a generic control polygon with segments of different length, as in Fig. 22, then we want each  $t_i$  to keep the same distance, in ratio, between the surrounding  $v_j$  and  $v_{j+1}$ , respect to the optimal case. For instance, in Fig. 21  $\frac{t_3 - v_1}{v_2 - v_1} = \frac{1}{4}$  and  $\frac{v_2 - t_3}{v_2 - v_1} = \frac{3}{4}$ , this means that in Fig. 22 the same values must be preserved.

The problem now is how to calculate the values of  $t_i$  in the general case. We consider only the inner part  $\tau$  of the partition vector, included the extremes

$$\tau_i = t_{i+m} \quad i = 0, \dots, n-m+1$$

where  $\tau_0 = a = 0$  and  $\tau_{n-m+1} = b = 1$ . In Fig. 21 and Fig. 22  $\tau = (t_2, t_3, t_4, t_5, t_6)$ . Now we calculate the positions of all  $\tau_i$  respect to the

<sup>12</sup>  $v_0$  is projected to  $a$ ,  $v_5$  is projected to  $b$ , and the ratios between the distances between vertices are preserved.

$v_j$  in the optimal case. We can achieve that using as unit the uniform distance  $v_j - v_{j-1}$  to calculate the positions of  $\tau_i$ . We specifically calculate

$$\tau_i^v = \frac{n}{n-m+1} \cdot i \quad i = 0, \dots, n-m+1 \quad (36)$$

obtaining the numbers  $\tau_i^v$  whose integer part  $\lfloor \tau_i^v \rfloor$  represents the index  $j$  of the  $v_j$  that is to the left of  $\tau_i$ , and the decimal part  $(\tau_i^v - \lfloor \tau_i^v \rfloor)$  represents the distance from it:  $\frac{\tau_i^v - \lfloor \tau_i^v \rfloor}{v_{j+1} - v_j}$ .

Now we calculate the projections  $v_i$  in the *generic* case. We start calculating the incremental distances between the vertices

$$\begin{cases} d_0 = 0 \\ d_i = d_{i-1} + \|v_i - v_{i-1}\|_2 \end{cases} \quad i = 1, \dots, n$$

and, remembering that the parametric domain is  $[0, 1]$ , we have

$$v_i = \frac{d_i}{d_n} \quad i = 0, \dots, n. \quad (37)$$

Using the positions in Eq. (36) on the projection in Eq. (37), we obtain the values

$$\tau_i = v_{\lfloor \tau_i^v \rfloor} + (\tau_i^v - \lfloor \tau_i^v \rfloor)(v_{\lfloor \tau_i^v \rfloor + 1} - v_{\lfloor \tau_i^v \rfloor}) \quad i = 0, \dots, n-m+1.$$

Finally, adding the duplicated knots, we obtain

$$t_i = \tau_{\min(n-m+1, \max(0, i-m))} \quad i = 0, \dots, n+m+1.$$

## 5.5 POST PROCESSING

The purpose of the post processing phase is to try to simplify the path  $P = (v_0, \dots, v_n)$  obtained in the previous phase removing useless vertices, in order to achieve a smoother path.

To obtain this, we realize Algorithm 8 that iterates through all the vertices, except the extremes, and checks if each  $v_i$  can be removed without consequences. With consequences we mean that removing  $v_i$  would cause a triangle in  $P$  to intersect one of the OTFs.

To clarify the concept, consider the simplification in 2-dimensional space in Fig. 23. The path to process is

$$P = (\dots, v_{i-2}, v_{i-1}, v_i, v_{i+1}, v_{i+2}, \dots)$$

**Algorithm 8** Post processing algorithm on path P.

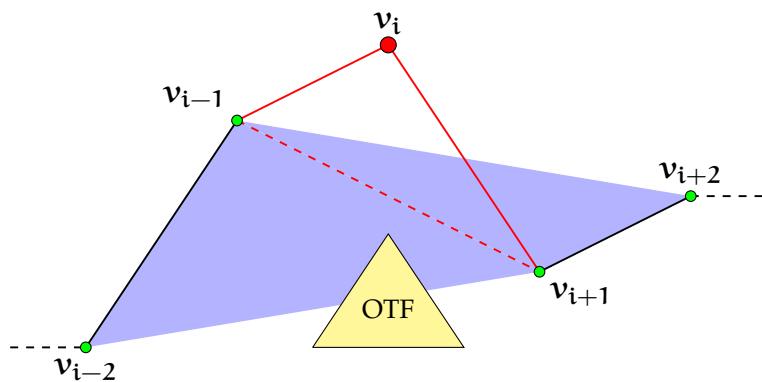
---

```

1: procedure POSTPROCESS(P)
2:   for  $i \leftarrow 1, n - 1$  do
3:     if  $i = 1$  or not intersectOTF( $\triangle v_{i-2}v_{i-1}v_{i+1}$ ) then
4:       if  $i = n - 1$  or not intersectOTF( $\triangle v_{i-1}v_{i+1}v_{i+2}$ ) then
5:          $P \leftarrow P \setminus \{v_i\}$ 
6:       end if
7:     end if
8:   end for
9: end procedure

```

---

Figure 23.: Example of post process check that removes  $v_i$ .

and we are considering removing  $v_i$  obtaining a modified path

$$\tilde{P} = (\dots, v_{i-2}, v_{i-1}, v_{i+1}, v_{i+2}, \dots).$$

Before doing this we need to check if any triangle in  $\tilde{P}$  intersects any OTF. In detail, we need to check only the two triangles  $\triangle v_{i-2}v_{i-1}v_{i+1}$  and  $\triangle v_{i-1}v_{i+1}v_{i+2}$  because the other triangles in  $\tilde{P}$  are already present in  $P$ . For instance the obstacle in the figure do not intersects any of the triangles in  $P$ , but it intersects  $\triangle v_{i-2}v_{i-1}v_{i+1}$  in  $\tilde{P}$ .

### 5.5.1 Complexity considerations

We need to check if two triangles intersect with an OTF for every vertex of  $P$ , hence we have a complexity of

$$\mathcal{O}(|P| \cdot |O|) = \mathcal{O}(|O|^2)$$

where  $O$  is the set of obstacles and  $|P|$  is the number of vertices in  $P$ .

## 5.6 THIRD SOLUTION: SIMULATED ANNEALING

The solutions in Section 5.2.1 and Section 5.2.2 have two problems in common:

- both reject configurations in a prudent way considering only the control polygon;
- and both do not optimize neither length nor other quantities.

These solutions have also the following benefits:

- they produce paths that are obstacle-free from construction;
- the application of the post-processing often produces a reduction in the curve length.

In this section, we describe a third approach based on probabilistic computation.

We can consider the problem of finding the shortest path as a constrained optimization problem, in which a certain configuration of the control vertices (and consequently the B-spline) is the state of the system, and we aim to minimize both the length of the control polygon (and

therefore the B-spline<sup>13)</sup> and the peak in curvature and torsion of the B-spline, under the constraint that the B-spline must not intersect the obstacles. We are interested in optimizing the length of the curve and the maximum peaks of both curvature and torsion, because we want a path that is short but also fair.

### 5.6.1 Lagrangian Relaxation (LR) applied to the project

We can apply the concept explained in Section 3.4.4 to the project.

The variable space  $X$  is composed of all the possible configurations of the path, or, in other words, it is defined by all the possible values of the vector  $P = (v_1, \dots, v_n)$  of all  $n$  ordered vertices  $v_i = (x_i, y_i, z_i)$  of the path. The Problem 13 can be formulated as follows:

$$\begin{aligned} & \underset{P}{\text{minimize}} \quad \alpha \cdot \text{maxCurv}(P) + \beta \cdot \text{maxTors}(P) + \gamma \cdot \text{normLen}(P) \\ & \text{subject to} \quad \left| \text{bspline}(P) \cap \bigcup_{i \in I} \text{obstacle}_i \right| = 0, \end{aligned}$$

where  $\text{maxCurv}(P)$  is the curvature peak of the B-spline constructed using  $P$  as control polygon,  $\text{maxTors}(P)$  is the absolute value of the torsion peak and  $\text{normLen}(P)$  is the length of the control polygon  $P$  normalized as a percentage of the length of the initial status<sup>14</sup>.  $\alpha$ ,  $\beta$  and  $\gamma$  are fixed coefficients used to give different weights to the curvature peak, torsion peak and length during the optimization process. The normalization of length is necessary to decouple the weight of the length from the length of the path.

Curvature and torsion are obtained in a discrete form. The B-spline curve is tabulated in a number of points that depends on the length of  $P$  by a multiplied constant, then for each point the curvature and torsion values are calculated.

Regarding the constraint,  $\text{bspline}(P)$  is the set of points of the *B-spline*, using  $P$  as control polygon, and  $\text{obstacle}_i$  is the area of the  $i^{\text{th}}$  of  $m$  obstacles, and  $I = \{1, \dots, m\}$ .

---

<sup>13</sup> We give to the users also the possibility of selecting the arc length as the quantity to minimize.

<sup>14</sup> If the user chooses to minimize the arc length, then  $\text{normLen}(P)$  becomes the length of the B-spline curve.

Thus, we need to build the Lagrangian function corresponding to Eq. (14). The constraint function is not negative and is calculated as the ratio

$$\text{constraint}(P) = \frac{|\{p \in \text{spline}(P) : \exists i \text{ s.t. } p \in \text{obstacle}_i\}|}{|\{\mathbf{p} \in \text{spline}(P)\}|}. \quad (38)$$

The points  $\mathbf{p}$  of the spline are calculated in a discrete form, like curvature and torsion. Thus, the constraint depends on the tabulation of the curve and it is also possible to have borderline cases where the constraint does not reflect the real situation<sup>15</sup>.

The function in Eq. (38) is not negative, thus the Lagrangian function, corresponding to Eq. (14), is

$$L_d(P, \lambda) = \text{gain}(P) + \lambda \cdot \text{constraint}(P) \quad (39)$$

where, for convenience,

$$\text{gain}(P) = \alpha \cdot \text{maxCurv}(P) + \beta \cdot \text{maxTors}(P) + \gamma \cdot \text{normLen}(P). \quad (40)$$

### 5.6.2 Annealing phase

The purpose of the simulated annealing phase is to find the minimum saddle point in the curve represented by the Eq. (39).

The Algorithm 9 is the annealing process, and its input is the initial status of the system  $x$  - i.e. the initial configuration of the control polygon. It operates this way:

1.  $\lambda$  and the temperature are initialized on Line 2 and Line 3 respectively;
2. the *while* on Line 4 is the main loop and the terminating condition is given by a minimum temperature or a minimum variation of energy between two iterations;
3. the *for* at Line 5 repeats the annealing move for a certain number of trials, on each iteration the algorithm probabilistically tries to make a move of the state of the system;
  - first, on Line 6, it chooses between moving in the Lagrangian space or in the space of the path;

---

<sup>15</sup> For instance, if we have very thin obstacles, a curve can pass through them having only few points (or even none) inside.

---

**Algorithm 9** Annealing
 

---

```

1: procedure ANNEALING( $x$ )
2:    $\lambda \leftarrow \text{initialLambda}$ 
3:    $T \leftarrow \text{initialTemperature}$ 
4:   while not terminationCondition() do
5:     for all number of trials do
6:       changeLambda  $\leftarrow$  True with changeLambdaProb
7:       if changeLambda then
8:          $\lambda' \leftarrow \text{neighbour}(\lambda)$ 
9:          $\lambda \leftarrow \lambda'$  with probability  $e^{-(|\text{energy}(x,\lambda) - \text{energy}(x,\lambda')|)/T}$ 
10:      else
11:         $x' \leftarrow \text{neighbour}(x)$ 
12:         $x \leftarrow x'$  with probability  $e^{-(|\text{energy}(x',\lambda) - \text{energy}(x,\lambda)|)/T}$ 
13:      end if
14:    end for
15:     $T \leftarrow T \cdot \text{warmingRatio}$ 
16:  end while
17: end procedure
  
```

---

- after that, based on the previous choice, the algorithm probabilistically tries to move the system in a neighbouring state: in the Lagrangian space at Line 8 or in the path space at Line 11;
4. finally, at the end of every trial set, at Line 15, the temperature  $T$  is cooled by a certain factor.

The termination condition in Line 4 is triggered by a minimum variation of energy  $\Delta\text{energy}$  between two consecutive iterations of the cycle. The termination is also triggered when a minimum temperature is reached, this happens to impose a limit on the number of cycles.

The choice of the neighbour is probabilistic. If the energy increases in the Lagrangian space or decreases in the path space, then the probability of choosing the new state is 1. If the energy decreases in the Lagrangian space or increases in the path space, then the new state is accepted with a probability that is:

$$\exp\left(-\frac{\Delta\text{energy}}{T}\right).$$

The neighbour function depends on the input:

- a neighbour of  $\lambda$  is a value that is equal to  $\lambda$  plus a uniform perturbation in range  $[-\text{maxLambdaPert}, \text{maxLambdaPert}]$ ;

- a neighbour of the path is obtained by randomly picking one of the vertices  $v_i$  (except the extremes  $v_0$  and  $v_n$ ), then uniformly choosing a direction and a distance in a specific range and, finally, moving  $v_i$  by the chosen values.

The energy function is equivalent to  $L_d$  in the Eq. (39):

$$\text{energy}(x, \lambda) = \text{gain}(P) + \lambda \cdot \text{constraint}(P). \quad (41)$$

The annealing process finds a saddle point by probabilistically increasing the energy when  $\lambda$  is moved, and decreasing the energy when the points are moved.

#### 5.6.2.1 Complexity considerations

For this solution, we still have the costs of Eq. (20) and Eq. (23) for the creation and pruning of the graph  $G$ . In addition, we need to apply Dijkstra's algorithm in  $G$  to obtain the initial path  $P$  with the cost of Eq. (31).

Regarding the annealing phase, for each *step* (an iteration of Line 4 in Algorithm 9) we have a fixed number of *trials* (the iterations of Line 5). For each trial, we need to calculate the value of the energy of Eq. (41) that is the sum of the gain and the constraint.

For the gain of Eq. (40) we need to calculate the values of curvature and torsion for every tabulated point. Furthermore, there is also a cost<sup>16</sup> of  $\mathcal{O}(|P|)$  to calculate the length of the control polygon. Thus, the cost for calculating the gain is

$$\mathcal{O}(|Sp| + |P|)$$

where  $Sp$  is the set of the tabulated points of the curve. The number of points in  $Sp$  depends on the length of the control polygon  $\text{len}(P)$ . Thus, we have a cost of  $\mathcal{O}(\text{len}(P) + |P|)$ , but in the worst case  $|P| = \mathcal{O}(|V|) = \mathcal{O}(|O|)$ , thus the cost is

$$\mathcal{O}(\text{len}(P) + |P|) = \mathcal{O}(\text{len}(P) + |O|). \quad (42)$$

In regards to the constraint of Eq. (38), we need to calculate if every point of the curve is inside an obstacle. This means a cost of

$$\mathcal{O}(\text{len}(P)|O|). \quad (43)$$

---

<sup>16</sup> Only if the users do not choose to minimize the arc length.

Hence, the total cost for the calculation of the annealing phase is

$$\mathcal{O}(\#steps \cdot \#trials \cdot (\text{len}(P)|O|)),$$

but the number of steps and trials are bounded by constants<sup>17</sup>. Thus, the cost becomes

$$\mathcal{O}(\text{len}(P)|O|). \quad (44)$$

The total cost for the solution is

$$\mathcal{O}(k|O|^2 + \text{len}(P)|O|). \quad (45)$$

Similarly to the previous solutions, if we have that  $k$  is a constant then the total cost becomes

$$\mathcal{O}(|O|^2 + \text{len}(P)|O|). \quad (46)$$

Description	Cost	Reference
Creation of G	$\mathcal{O}( O  \log  O )$	Eq. (20)
Pruning of G	$\mathcal{O}(k O ^2)$	Eq. (23)
Routing in G	$\mathcal{O}(k O  +  O  \log  O )$	Eq. (31)
Gain	$\mathcal{O}(\text{len}(P) +  P ) = \mathcal{O}(\text{len}(P) +  O )$	Eq. (42)
Constraint	$\mathcal{O}(\text{len}(P) O )$	Eq. (43)
Annealing	$\mathcal{O}(\text{len}(P) O )$	Eq. (44)
Total	$\mathcal{O}(k O ^2 + \text{len}(P) O )$	Eq. (45)
Total (k constant)	$\mathcal{O}( O ^2 + \text{len}(P) O )$	Eq. (46)

Table 4.: Summary of the costs for solution three

In Table 4 we summarize all the costs. It is difficult to quantitatively compare the cost of this solution with the previous ones. This is due to the presence of the factor  $\text{len}(P)$  that depends on the geometry of the scene. however, we can affirm that this solution is more complex than the previous two by a term  $\mathcal{O}(\text{len}(P)|O|)$ .

Furthermore, in this solution we can divide the algorithm in two parts:

1. first we can construct G with cost  $\mathcal{O}(|O|^2)$ ;
2. then we can use it for different scenarios with cost  $|O| \log |O| + \text{len}(P)|O|$ .

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<sup>17</sup> Although such constants can be very high.

**Part III**

**EVALUATION**



# 6

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## CODE STRUCTURE

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We designed the code with an Object Oriented Programming (OOP) methodology in Python 3 (<https://www.python.org/>). A versatile language with a strong appeal on scientific community, easy to learn and with an increasing active community of developers behind. We relied on SciPy (<https://www.scipy.org/>) and NumPy (<http://www.numpy.org/>) libraries for taking care of different numerical methods. Furthermore we used NetworkX library (<http://networkx.github.io/>) to represent graphs and to route in them. Regarding the graphic output we used VTK (<http://www.vtk.org/>) bindings in Python.

The main class is `Voronizerator`, it maintains the status of the scene and provides all the methods for the interface with users.

- `addBoundingBox` is used for adding a bounding box at specified coordinates to the scene.
- `addPolyhedron` is used for adding a new obstacle to the scene, it required a `Polyhedron` object as argument.
- `setPolyhedronsSites` add the sites for the VD to the scene.
- The method `makeVoroGraph` is used for creating the graphs  $G$  and  $G_t$  using the algorithms described in Section 5.1.1 and Section 5.1.2.
- `setAdaptivePartition` and `setBsplineDegree` are used for selecting between uniform or adaptive knot partition, and for choosing the desired degree of the curve.
- `extractXmlTree` and `importXmlTree` are used for saving and restoring the scene in XML format.
- All the other methods `plot*` are used for drawing the different elements of the scene. They require a plotter as argument.

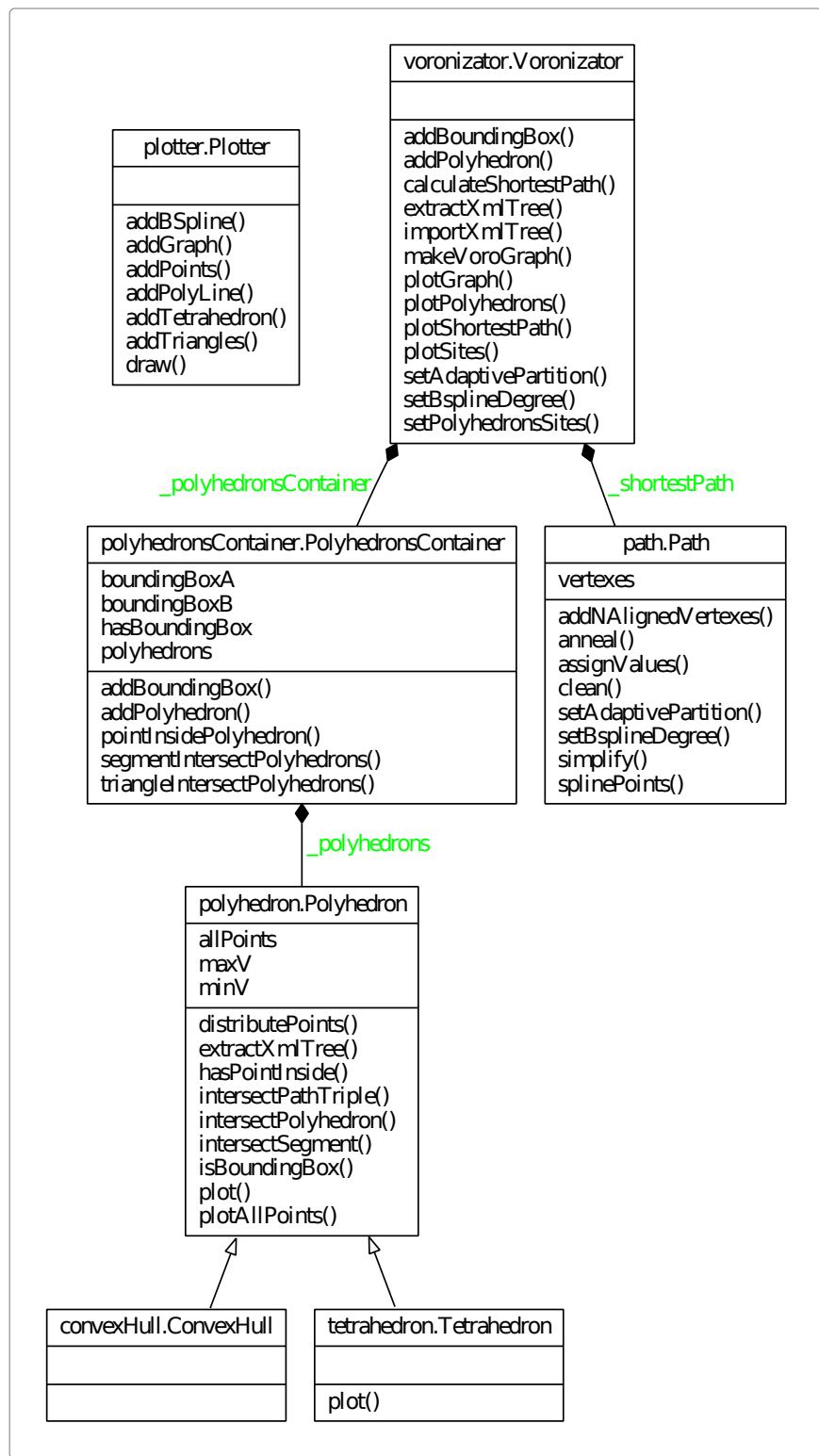


Figure 24.: Excerpt UML of the project

The class `Plotter` provides the interface for drawing all the necessary elements using VTK.

The class `Polyhedron` represents a single obstacle (that can also be one of the two subclasses `ConvexHull` and `Tetrahedron`). it provides all the necessary methods for performing geometry checks of point inclusion and intersection with segments, triangles, and other obstacles.

The class `Path` represents the control polygon of the curve. It provides the methods `addNAlignedVertexes` and `simplify` that perform respectively the degree increase (Section 5.3) and the post processing (Section 5.5). The method `clean` is necessary for the second solution described in Section 5.2.2. Furthermore this class provides also the functionality for optimizing the curve using the SA (Section 5.6) with the method `anneal`.

Furthermore we provide scripts for the creation of random scenes and for the execution of the different methods.



# 7

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## TESTING

---

For evaluating the project we made the tests summarized in Table 7, Table 8, Table 9, Table 10, where

- *Scene* refers to which scene of Table 5 was used;
- $s \rightarrow e$  indicates the starting and ending points
- *Deg.* is the degree of the B-spline curve;
- *Met.* is the method used, where
  - Method A is Dijkstra in  $G'$ ;
  - Method B is Dijkstra in  $G$ ;
  - Method C is Simulated Annealing;
- *P. p.* indicates if the post processing is used ( $\checkmark$ ) or not ( $\times$ );
- *Part.* indicates if the uniform knot partition (**U**) or the adaptive one (**A**) is used;
- *Config.* is used only for method C and indicates the used annealing configuration from Table 6.

The Table 5 gives some data about the scenes. The fields are the followings.

- *B.b. A* and *B.b. B* are the extremes of the bounding box.
- *Min. obs. rad.* and *Max. obs. rad.* are respectively the minimum radius and the maximum radius of the obstacles in the scene. For scenes 1, 1b, and 2 the obstacles are non-intersecting tetrahedrons generated randomly with the specific parameters. The scene 3 is a bucket-shaped obstacle with center in  $[0.5, 0.5, 0.5]$ , with width 0.2, height 0.4 and thickness 0.2.

- $\# obs.$  is the number of obstacles in the scene.
- $Max. empty area$  is the maximum empty area for the distribution of the Voronoi sites as explained in Section 5.1.1.

Table 6 indicates the configurations for the SA phase. The fields are the followings:

- $T_0$  is the initial *temperature*;
- *Trials* is the number of trials for each annealing cycle;
- *warm.* is the warming ratio of temperature between two consecutive cycles;
- *min T* is the minimum temperature at which the process terminates;
- *min ΔE* is the minimum difference of energy between two consecutive cycles at which the process terminates;
- $\lambda pert$  is the maximum perturbation of  $\lambda$  in every move;
- $V pert fact$  is the maximum perturbation of a path vertex in every move, expressed in fraction of the control polygon length;
- $\lambda_0$  is the initial value of  $\lambda$ ;
- $\lambda P$  is the probability of changing  $\lambda$  instead the path in each move;
- *Len type* indicates if it is considered the control polygon (poly) or the arc (arc) length as optimizing quantity;
- *Ratios* is a triple of *weights* that indicates the importance, during the optimization, of curvature, torsion and length respectively;

Scene	B.b. A	B.b. B	Min. obs. rad.	Max. obs. rad.	# obs.	Max. empty area
1	[−0.1, −0.1, −0.1]	[1.1, 1.1, 1.1]	0.2	0.4	10	0.1
1b	[−0.1, −0.1, −0.1]	[1.1, 1.1, 1.1]	0.2	0.4	10	0.01
2	[−0.1, −0.1, −0.1]	[1.1, 1.1, 1.1]	0.2	0.4	100	0.1
3	[0, 0, 0]	[1, 1, 1]	−	−	1	0.1

Table 5.: Testing scenes.

Config.	T <sub>0</sub>	Trials	warm.	min T	min ΔE	λ pert	V pert fact	λ <sub>0</sub>	λP	Len type	Ratios
1	10	10	0.7	1e-7	1e-6	1000	10	0	5e-2	arc	[0.1, 0.1, 0.8]
2	10	10	0.7	1e-7	1e-6	1000	10	0	5e-2	poly	[0.1, 0.1, 0.8]
2b	10	100	0.7	1e-7	1e-6	1000	100	0	5e-2	poly	[0.1, 0.1, 0.8]
3	10	10	0.7	1e-7	1e-6	1000	10	0	5e-2	arc	[0.3, 0.3, 0.4]
3b	10	10	0.9	1e-5	1e-6	1000	100	0	5e-2	arc	[0.3, 0.3, 0.4]

Table 6.: Annealing configurations.

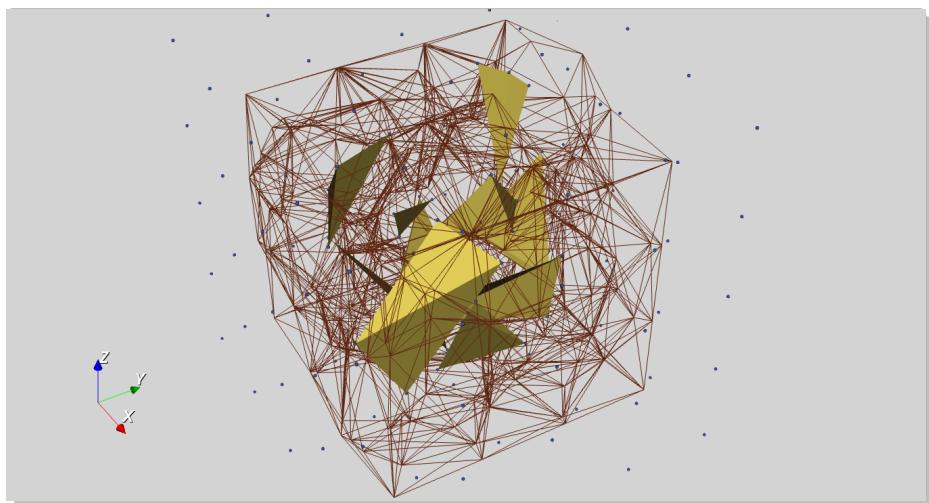


Figure 25.: Scene 1.

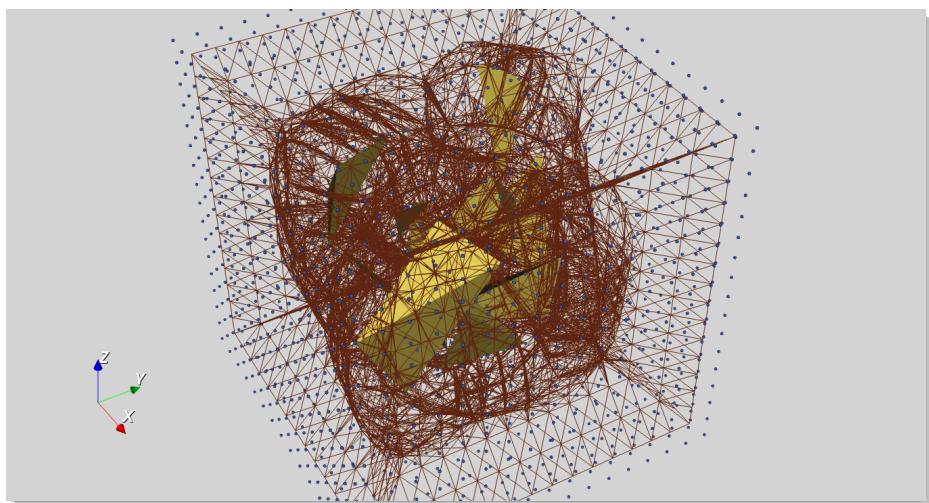


Figure 26.: Scene 1b.

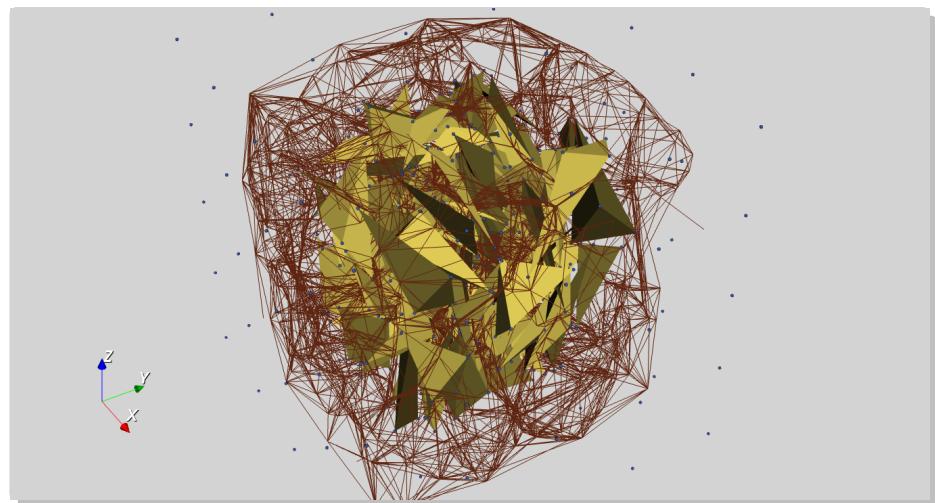


Figure 27.: Scene 2.

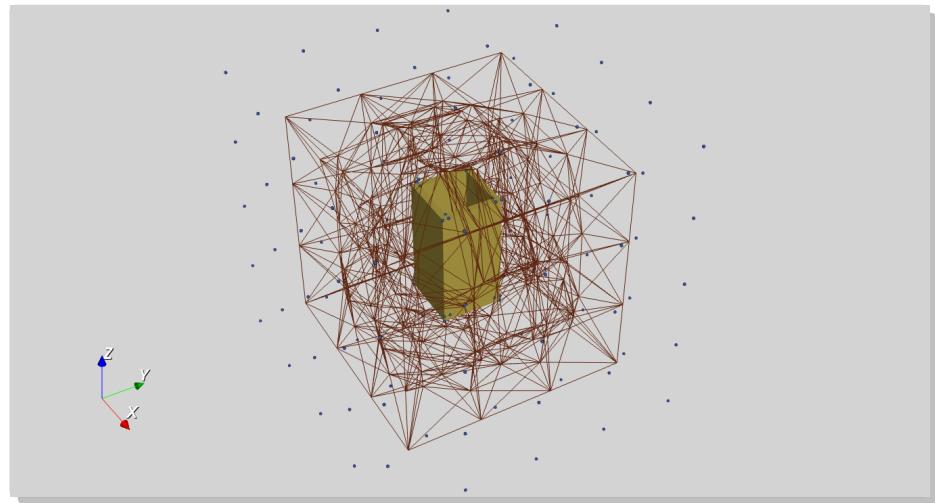


Figure 28.: Scene 3.

#	Scene	$s \rightarrow e$	Deg.	Met.	P. p.	Part.	Config.	figure
1	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	2	A	✗	U	-	Fig. 29
2	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	2	A	✓	U	-	Fig. 30
3	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	2	A	✗	A	-	Fig. 31
4	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	2	A	✓	A	-	Fig. 32
5	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	3	A	✗	U	-	Fig. 33
6	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	3	A	✓	U	-	Fig. 34
7	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	3	A	✗	A	-	Fig. 35
8	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	3	A	✓	A	-	Fig. 36
9	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	4	A	✗	U	-	Fig. 37
10	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	4	A	✓	U	-	Fig. 38
11	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	4	A	✗	A	-	Fig. 39
12	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	4	A	✓	A	-	Fig. 40
13	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	2	B	✗	U	-	Fig. 41
14	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	2	B	✓	U	-	Fig. 42
15	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	2	B	✗	A	-	Fig. 43
16	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	2	B	✓	A	-	Fig. 44
17	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	3	B	✗	U	-	Fig. 45
18	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	3	B	✓	U	-	Fig. 46
19	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	3	B	✗	A	-	Fig. 47
20	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	3	B	✓	A	-	Fig. 48
21	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	4	B	✗	U	-	Fig. 49
22	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	4	B	✓	U	-	Fig. 50
23	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	4	B	✗	A	-	Fig. 51
24	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	4	B	✓	A	-	Fig. 52

Table 7.: Summary of the tests.

#	Scene	$s \rightarrow e$	Deg.	Met.	P. p.	Part.	Config.	figure
25	1b	[0.2,0.2,0.2]→[0.9,0.9,0.9]	2	B	✗	U	-	Fig. 53
26	1b	[0.2,0.2,0.2]→[0.9,0.9,0.9]	2	B	✓	U	-	Fig. 54
27	1b	[0.2,0.2,0.2]→[0.9,0.9,0.9]	2	B	✗	A	-	Fig. 55
28	1b	[0.2,0.2,0.2]→[0.9,0.9,0.9]	2	B	✓	A	-	Fig. 56
29	1b	[0.2,0.2,0.2]→[0.9,0.9,0.9]	3	B	✗	U	-	Fig. 57
30	1b	[0.2,0.2,0.2]→[0.9,0.9,0.9]	3	B	✓	U	-	Fig. 58
31	1b	[0.2,0.2,0.2]→[0.9,0.9,0.9]	3	B	✗	A	-	Fig. 59
32	1b	[0.2,0.2,0.2]→[0.9,0.9,0.9]	3	B	✓	A	-	Fig. 60
33	1b	[0.2,0.2,0.2]→[0.9,0.9,0.9]	4	B	✗	U	-	Fig. 61
34	1b	[0.2,0.2,0.2]→[0.9,0.9,0.9]	4	B	✓	U	-	Fig. 62
35	1b	[0.2,0.2,0.2]→[0.9,0.9,0.9]	4	B	✗	A	-	Fig. 63
36	1b	[0.2,0.2,0.2]→[0.9,0.9,0.9]	4	B	✓	A	-	Fig. 64
37	2	[0.5,0.5,0.5]→[0.5,0.5,0.95]	2	B	✗	U	-	Fig. 65
38	2	[0.5,0.5,0.5]→[0.5,0.5,0.95]	2	B	✓	U	-	Fig. 66
39	2	[0.5,0.5,0.5]→[0.5,0.5,0.95]	2	B	✗	A	-	Fig. 67
40	2	[0.5,0.5,0.5]→[0.5,0.5,0.95]	2	B	✓	A	-	Fig. 68
41	2	[0.5,0.5,0.5]→[0.5,0.5,0.95]	3	B	✗	U	-	Fig. 69
42	2	[0.5,0.5,0.5]→[0.5,0.5,0.95]	3	B	✓	U	-	Fig. 70
43	2	[0.5,0.5,0.5]→[0.5,0.5,0.95]	3	B	✗	A	-	Fig. 71
44	2	[0.5,0.5,0.5]→[0.5,0.5,0.95]	3	B	✓	A	-	Fig. 72
45	2	[0.5,0.5,0.5]→[0.5,0.5,0.95]	4	B	✗	U	-	Fig. 73
46	2	[0.5,0.5,0.5]→[0.5,0.5,0.95]	4	B	✓	U	-	Fig. 74
47	2	[0.5,0.5,0.5]→[0.5,0.5,0.95]	4	B	✗	A	-	Fig. 75
48	2	[0.5,0.5,0.5]→[0.5,0.5,0.95]	4	B	✓	A	-	Fig. 76

Table 8.: Summary of the tests (continue).

#	Scene	$s \rightarrow e$	Deg.	Met.	P. p.	Part.	Config.	figure
49	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	2	A	✗	U	-	Fig. 77
50	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	2	A	✓	U	-	Fig. 78
51	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	2	A	✗	A	-	Fig. 79
52	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	2	A	✓	A	-	Fig. 80
53	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	3	A	✗	U	-	Fig. 81
54	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	3	A	✓	U	-	Fig. 82
55	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	3	A	✗	A	-	Fig. 83
56	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	3	A	✓	A	-	Fig. 84
57	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	4	A	✗	U	-	Fig. 85
58	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	4	A	✓	U	-	Fig. 86
59	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	4	A	✗	A	-	Fig. 87
60	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	4	A	✓	A	-	Fig. 88
61	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	2	B	✗	U	-	Fig. 89
62	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	2	B	✓	U	-	Fig. 90
63	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	2	B	✗	A	-	Fig. 91
64	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	2	B	✓	A	-	Fig. 92
65	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	3	B	✗	U	-	Fig. 93
66	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	3	B	✓	U	-	Fig. 94
67	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	3	B	✗	A	-	Fig. 95
68	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	3	B	✓	A	-	Fig. 96
69	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	4	B	✗	U	-	Fig. 97
70	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	4	B	✓	U	-	Fig. 98
71	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	4	B	✗	A	-	Fig. 99
72	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	4	B	✓	A	-	Fig. 100

Table 9.: Summary of the tests (continue).

#	Scene	$s \rightarrow e$	Deg.	Met.	P. p.	Part.	Config.	figure
73	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	2	C	-	U	1	Fig. 101
74	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	3	C	-	U	1	Fig. 102
75	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	4	C	-	U	1	Fig. 103
76	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	2	C	-	U	2	Fig. 104
77	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	3	C	-	U	2	Fig. 105
78	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	4	C	-	U	2	Fig. 106
79	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	2	C	-	U	3	Fig. 107
80	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	3	C	-	U	3	Fig. 108
81	1	[0.2,0.2,0.2]→[0.9,0.9,0.9]	4	C	-	U	3	Fig. 109
82	2	[0.5,0.5,0.5]→[0.5,0.5,0.95]	2	C	-	U	1	Fig. 110
83	2	[0.5,0.5,0.5]→[0.5,0.5,0.95]	3	C	-	U	1	Fig. 111
84	2	[0.5,0.5,0.5]→[0.5,0.5,0.95]	4	C	-	U	1	Fig. 112
85	2	[0.5,0.5,0.5]→[0.5,0.5,0.95]	2	C	-	U	2	Fig. 113
86	2	[0.5,0.5,0.5]→[0.5,0.5,0.95]	3	C	-	U	2	Fig. 114
87	2	[0.5,0.5,0.5]→[0.5,0.5,0.95]	4	C	-	U	2	Fig. 115
88	2	[0.5,0.5,0.5]→[0.5,0.5,0.95]	2	C	-	U	3	Fig. 116
89	2	[0.5,0.5,0.5]→[0.5,0.5,0.95]	3	C	-	U	3	Fig. 117
90	2	[0.5,0.5,0.5]→[0.5,0.5,0.95]	4	C	-	U	3	Fig. 118
91	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	2	C	-	U	1	Fig. 119
92	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	3	C	-	U	1	Fig. 120
93	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	4	C	-	U	1	Fig. 121
94	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	2	C	-	U	2b	Fig. 122
95	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	3	C	-	U	2b	Fig. 123
96	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	4	C	-	U	2b	Fig. 124
97	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	2	C	-	U	3b	Fig. 125
98	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	3	C	-	U	3b	Fig. 126
99	3	[0.5,0.5,0.4]→[0.5,0.5,0.2]	4	C	-	U	3b	Fig. 127

Table 10.: Summary of the tests (continue).

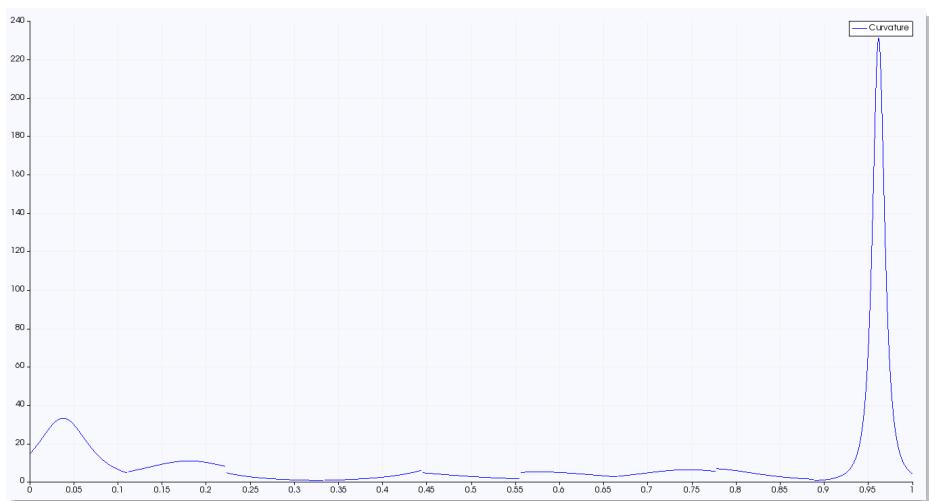
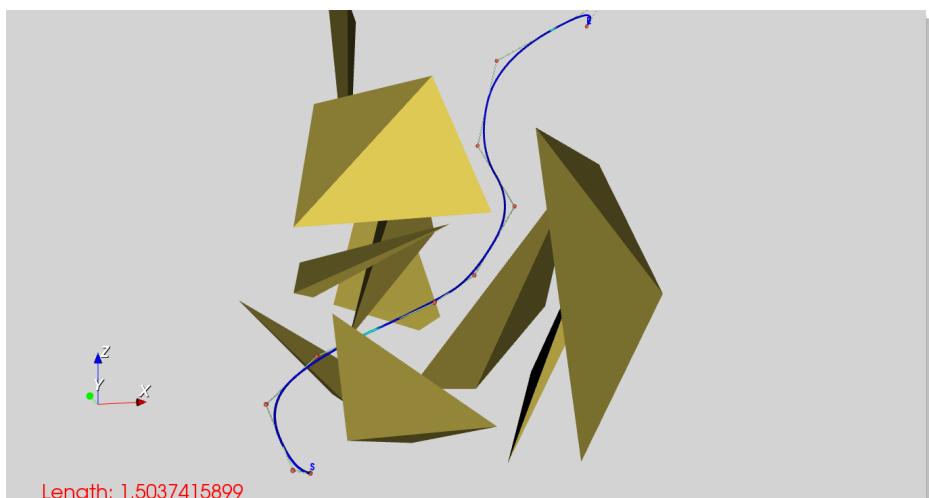
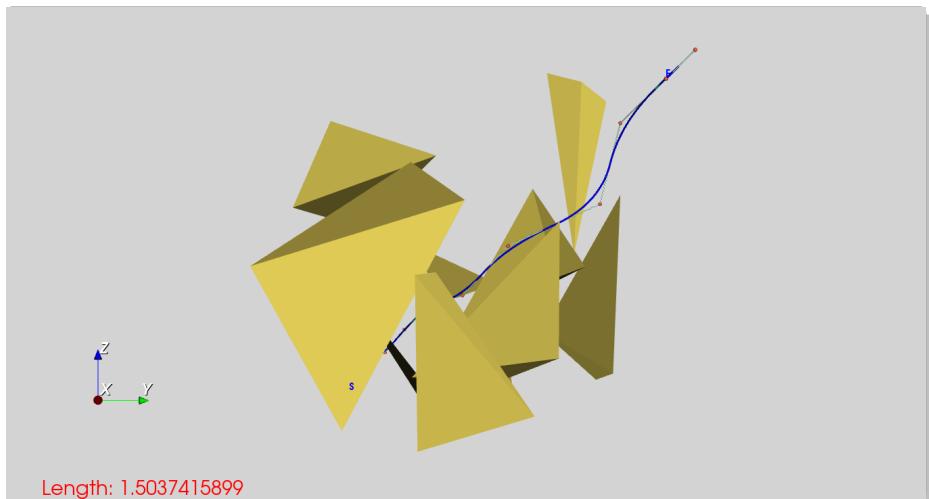


Figure 29.: Test 1; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 2; Meth. A; Post proc. X; Part. U.

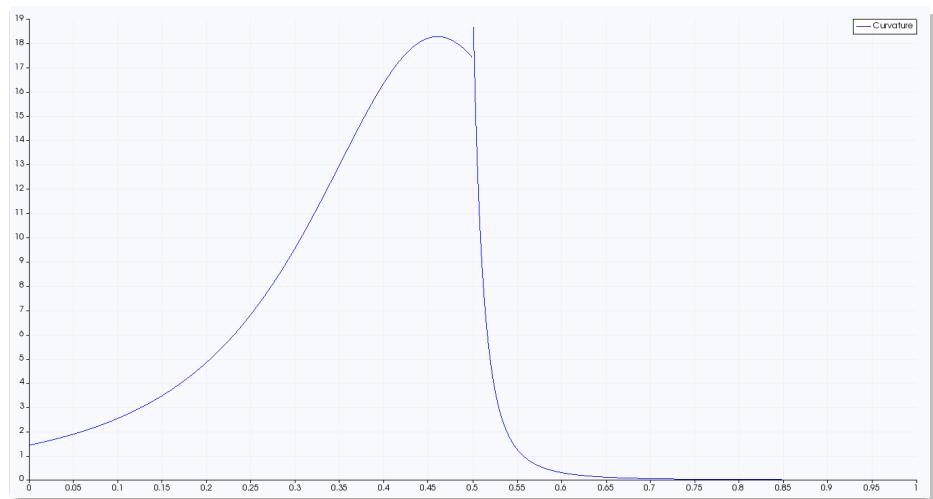
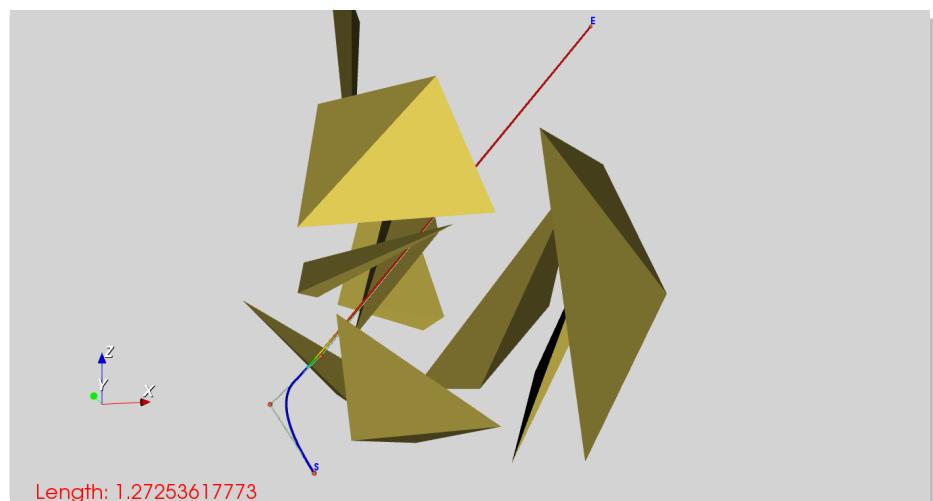
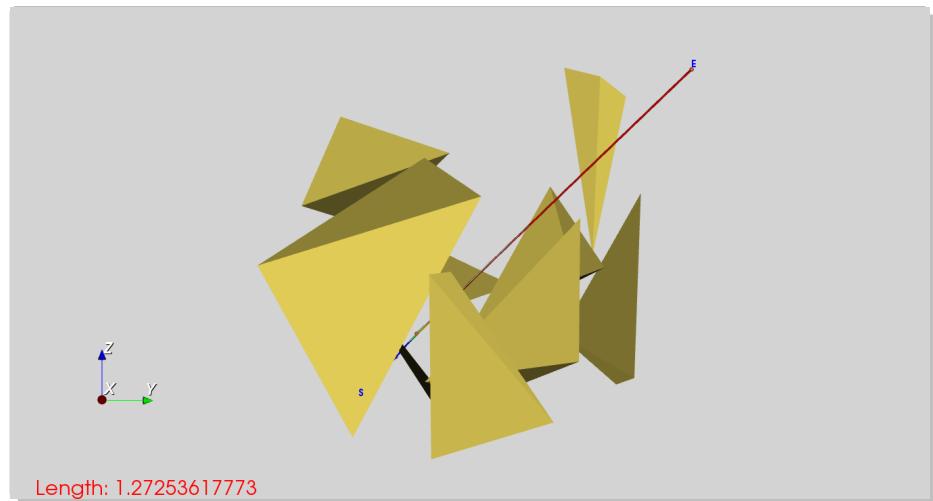


Figure 30.: Test 2; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 2; Meth. A; Post proc. ✓; Part. U.

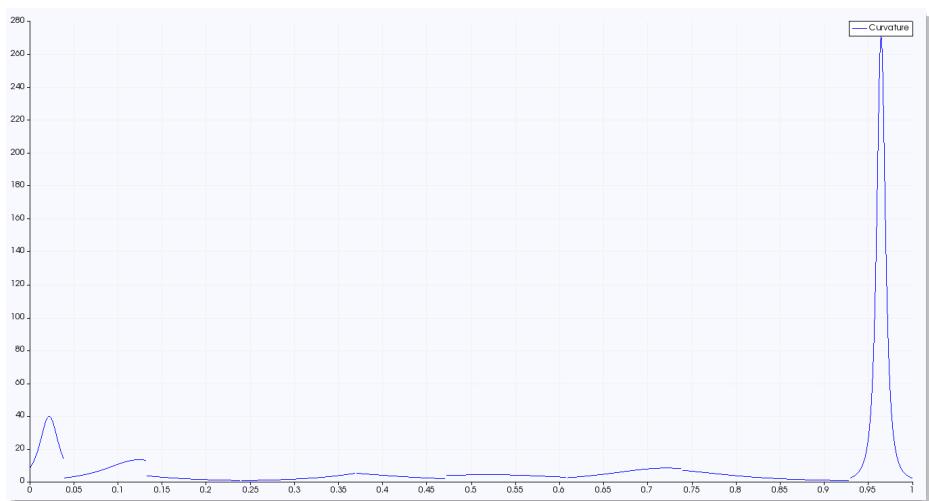
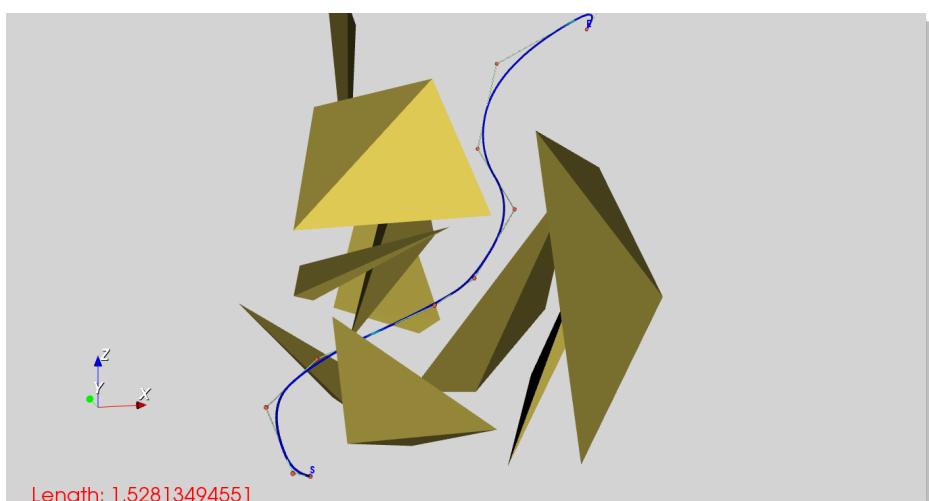
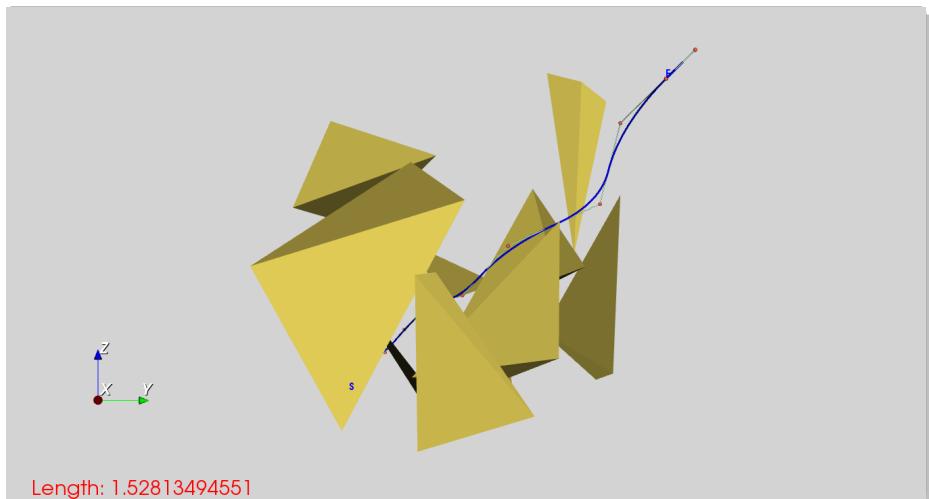


Figure 31.: Test 3; Scene 1;  $s \rightarrow e$   $[0.2,0.2,0.2] \rightarrow [0.9,0.9,0.9]$ ; Deg. 2; Meth. A; Post proc. X; Part. A.

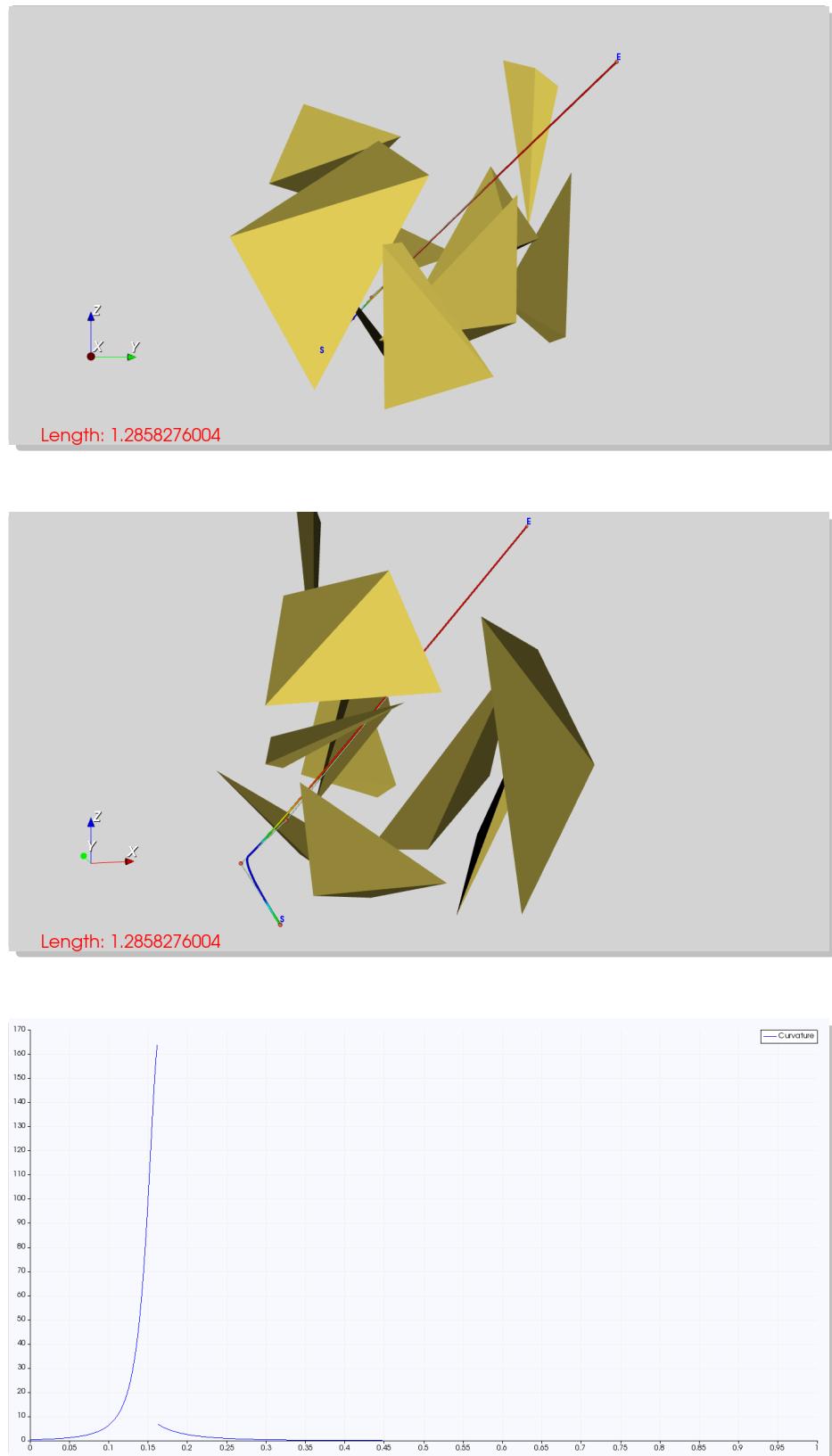


Figure 32.: Test 4; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 2; Meth. A; Post proc. ✓; Part. A.

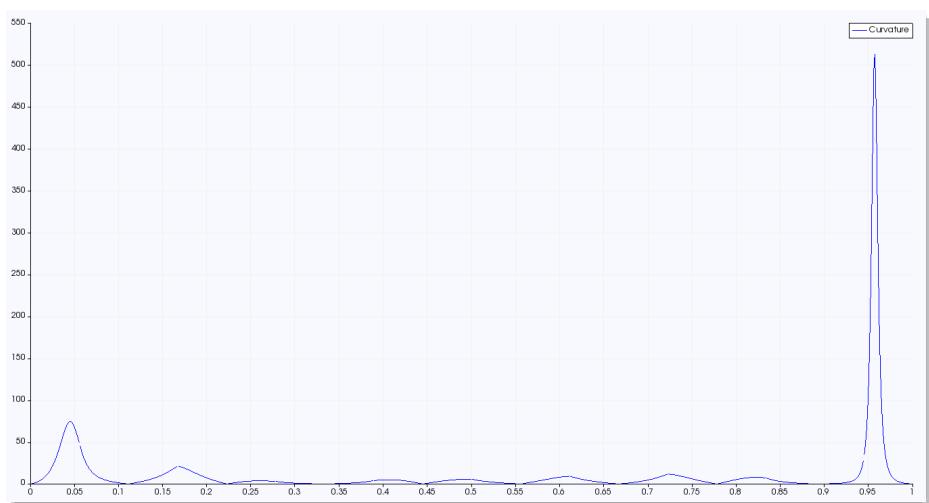
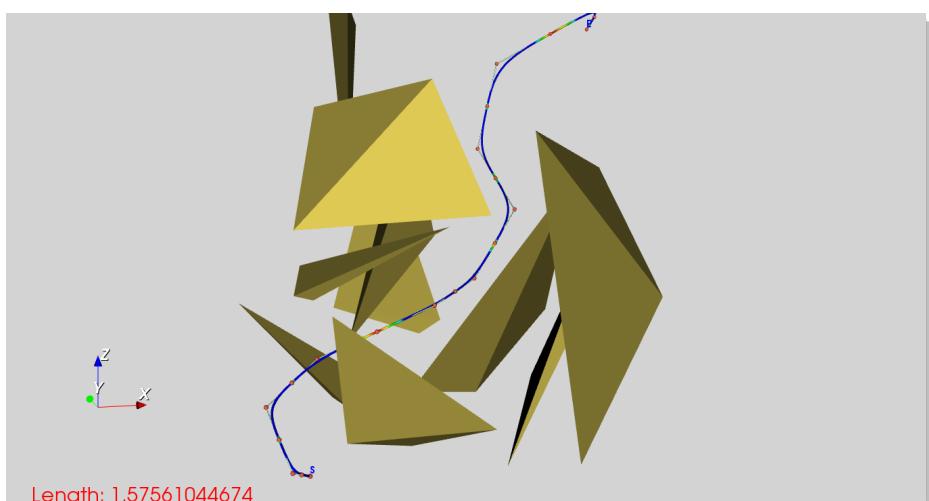
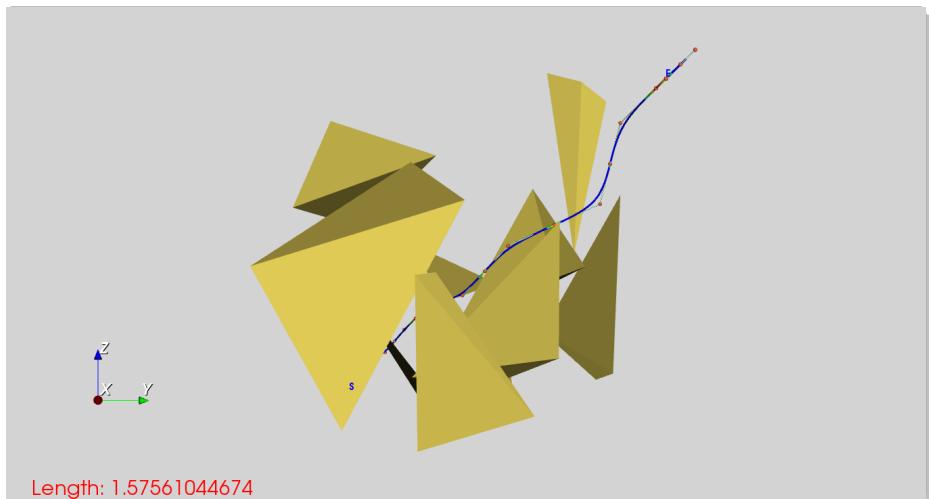


Figure 33.: Test 5; Scene 1;  $\mathbf{s} \rightarrow \mathbf{e}$   $[0.2,0.2,0.2] \rightarrow [0.9,0.9,0.9]$ ; Deg. 3; Meth. A; Post proc. X; Part. U.

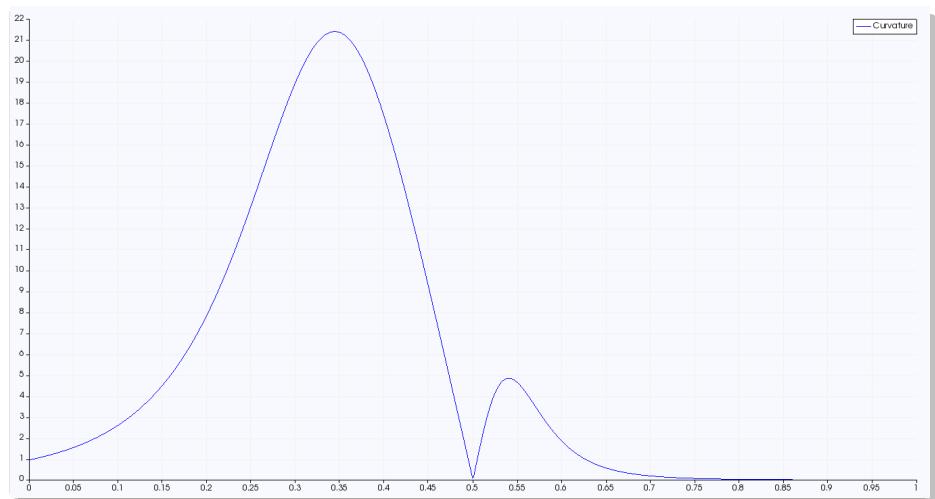
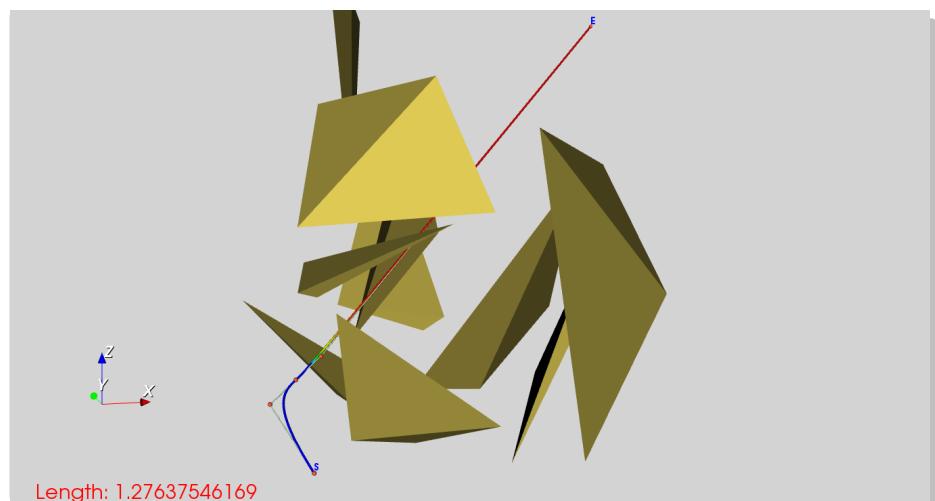
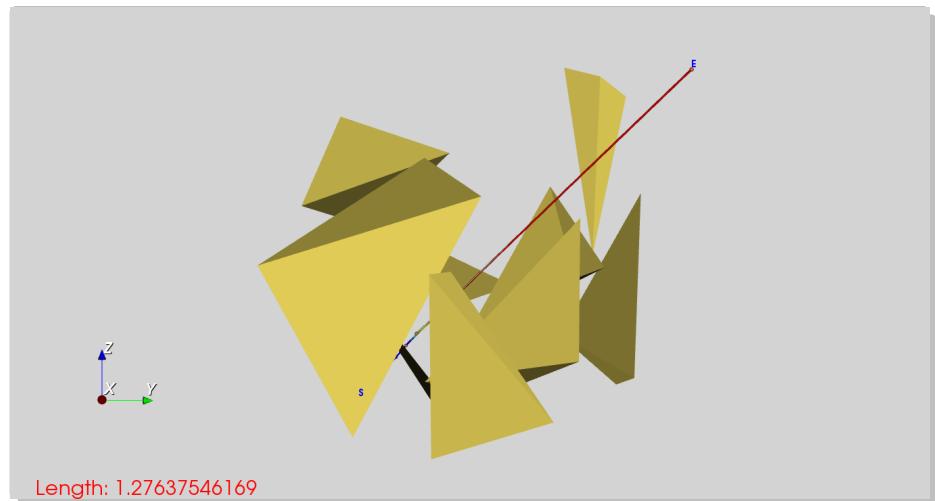


Figure 34.: Test 6; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 3; Meth. A; Post proc. ✓; Part. U.

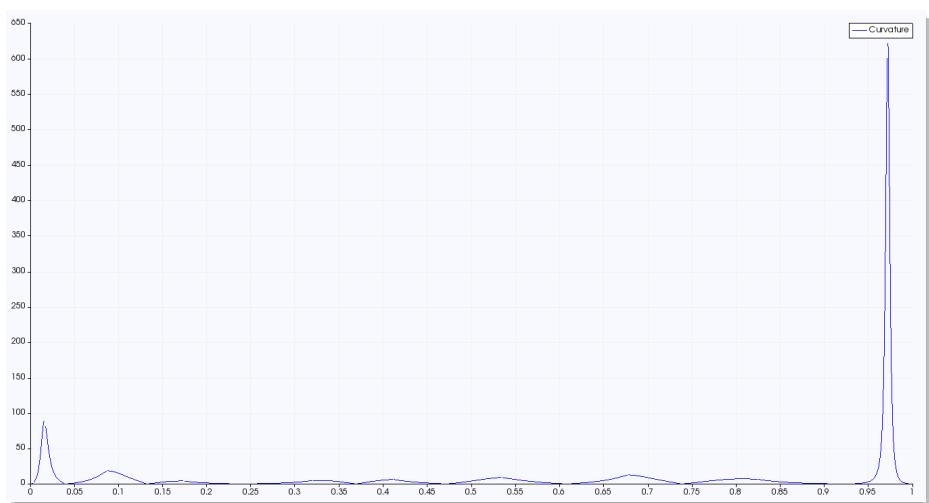
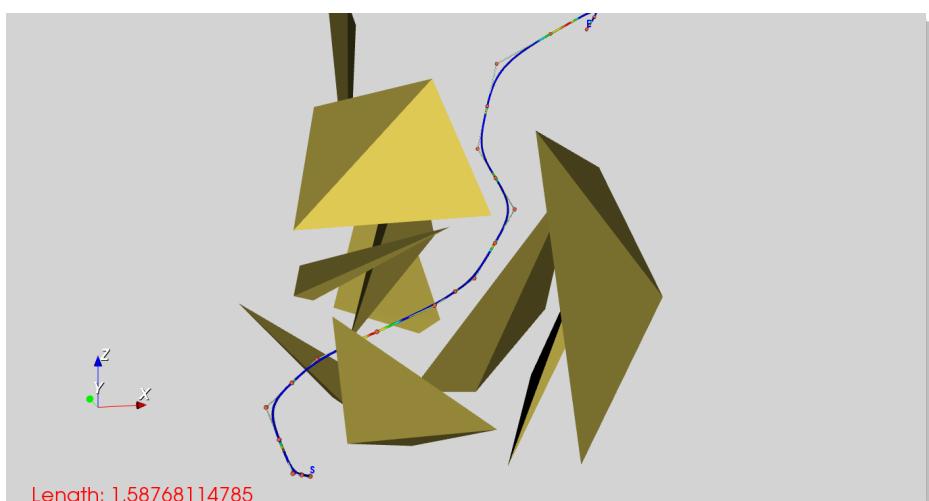
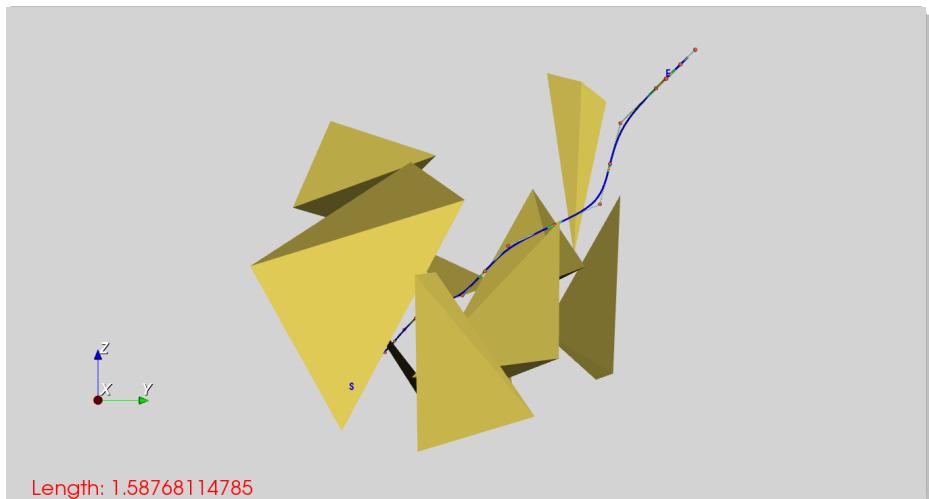


Figure 35.: Test 7; Scene 1;  $s \rightarrow e$   $[0.2,0.2,0.2] \rightarrow [0.9,0.9,0.9]$ ; Deg. 3; Meth. A; Post proc. X; Part. A.

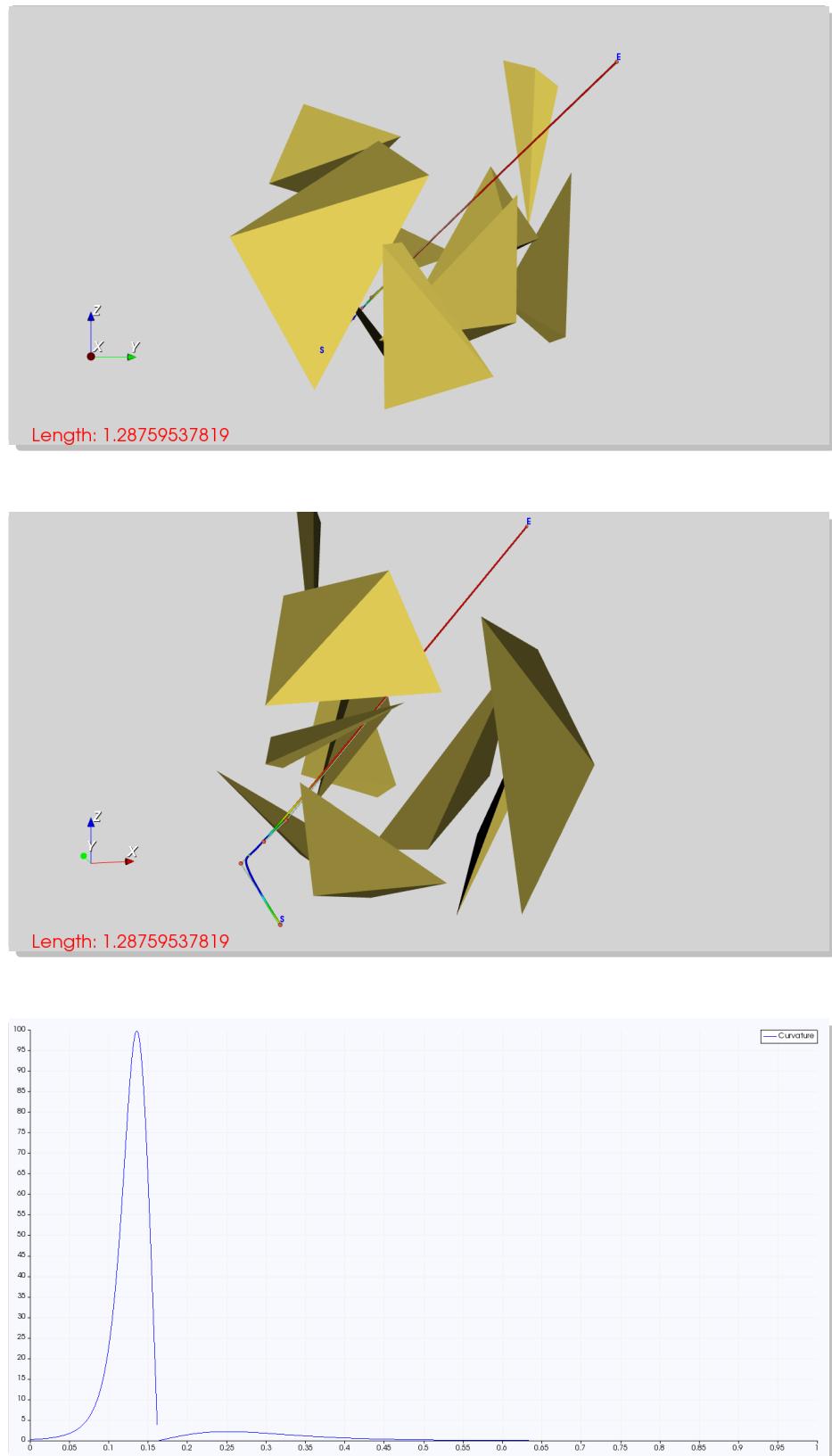


Figure 36.: Test 8; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 3; Meth. A; Post proc. ✓; Part. A.

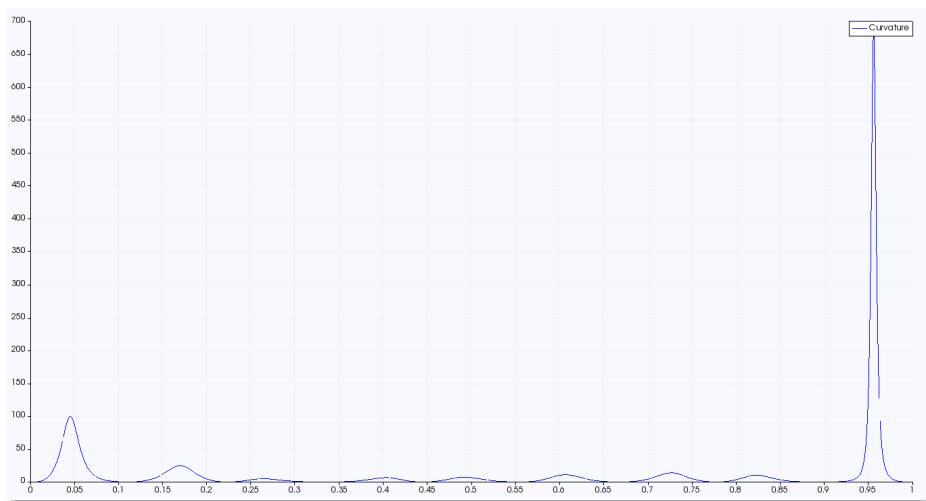
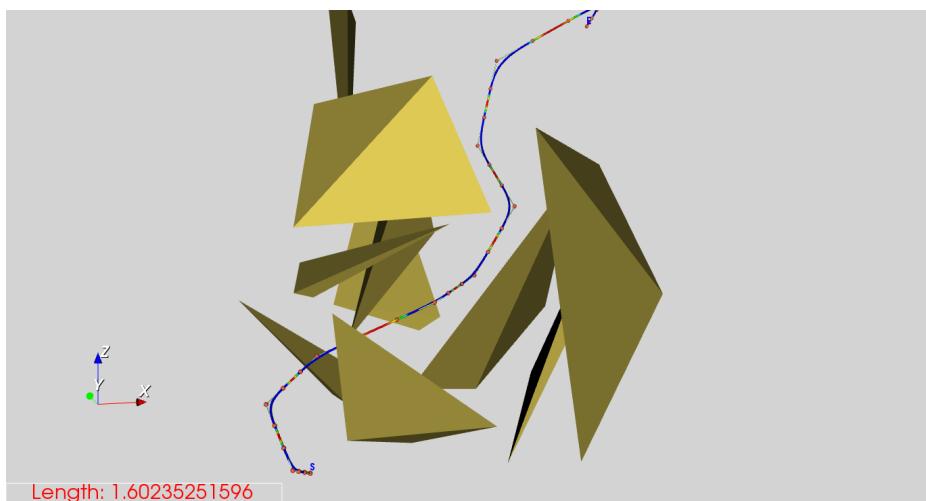
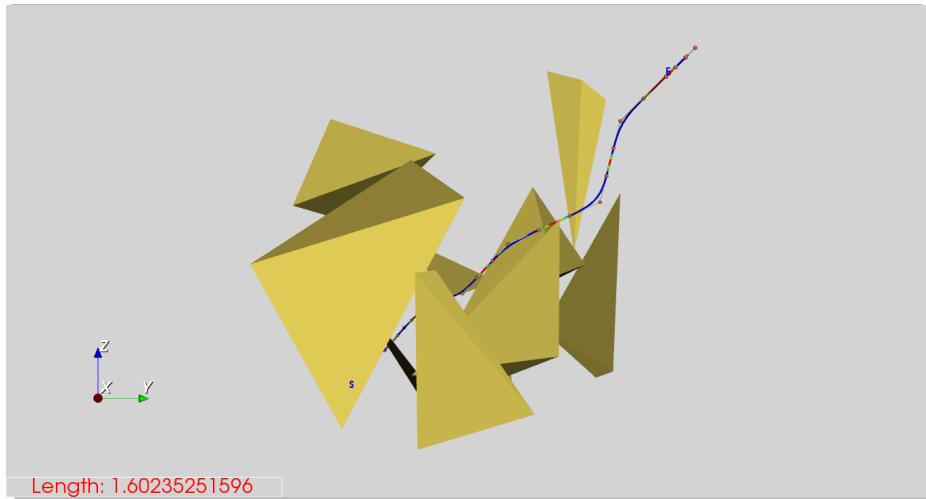


Figure 37.: Test 9; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 4; Meth. A; Post proc. X; Part. U.

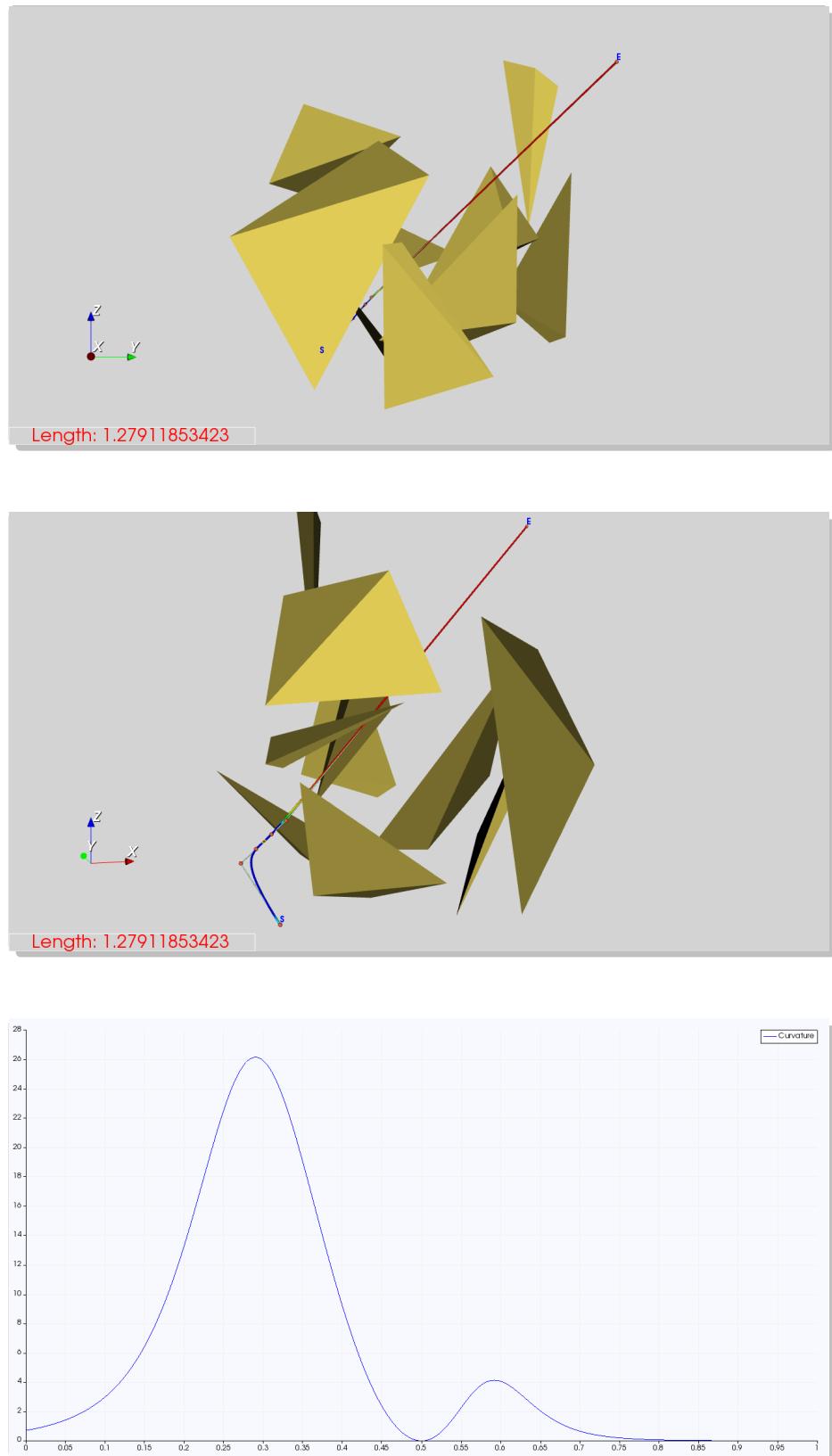


Figure 38.: Test 10; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 4; Meth. A; Post proc. ✓; Part. U.

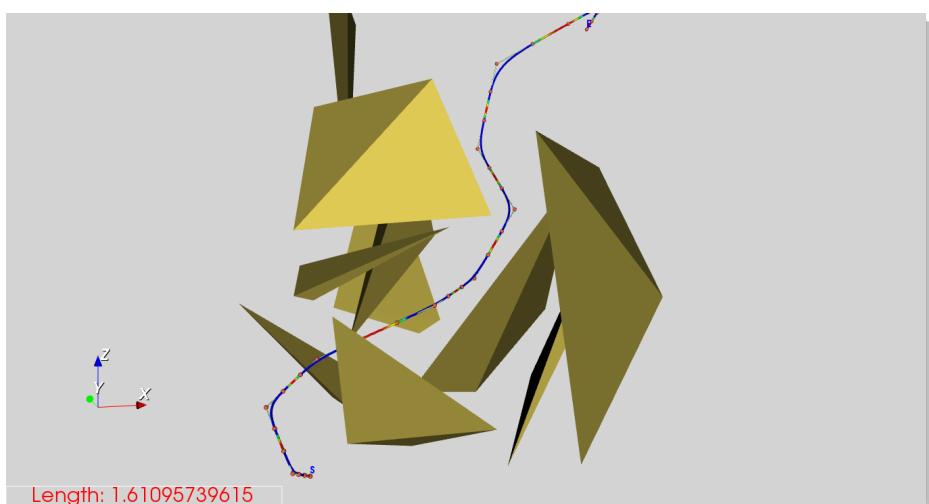
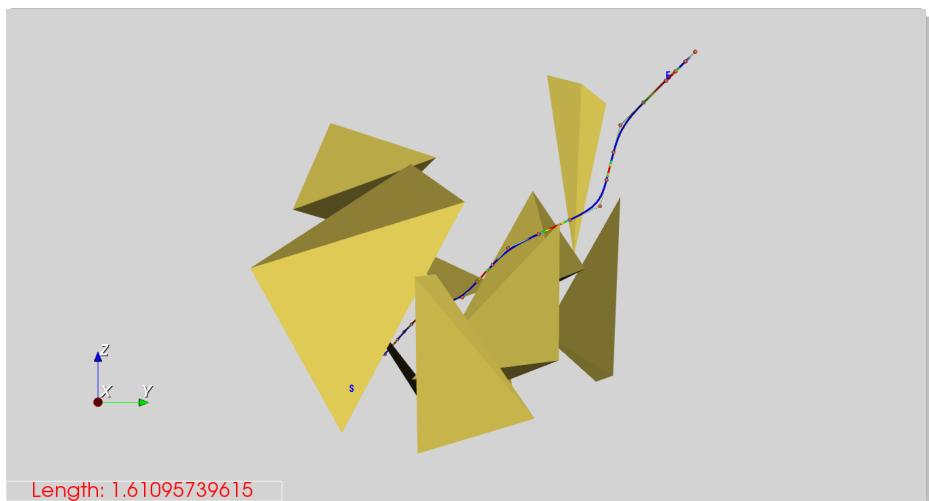


Figure 39.: Test 11; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 4; Meth. A; Post proc. X; Part. A.

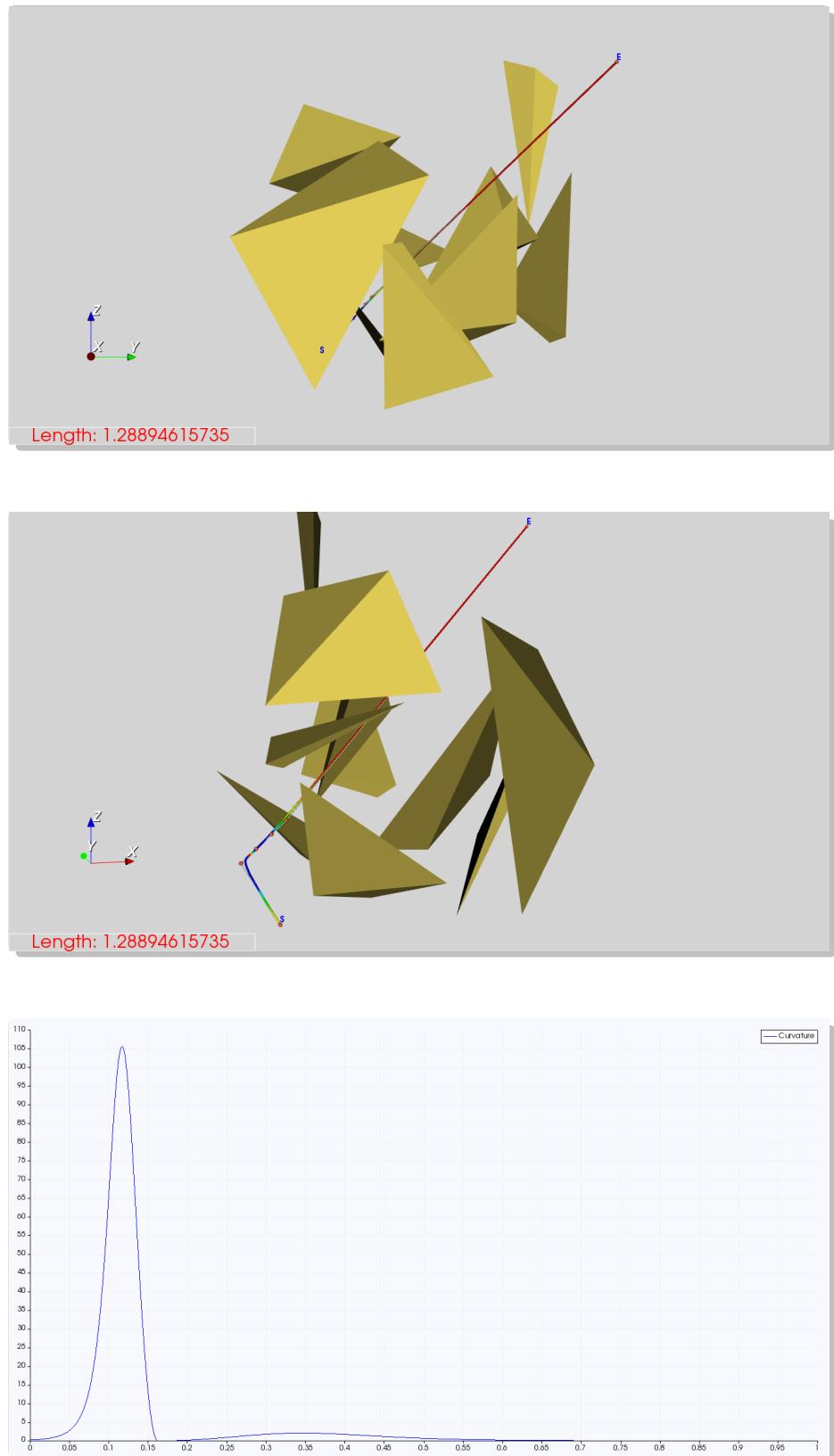


Figure 40.: Test 12; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 4; Meth. A; Post proc. ✓; Part. A.

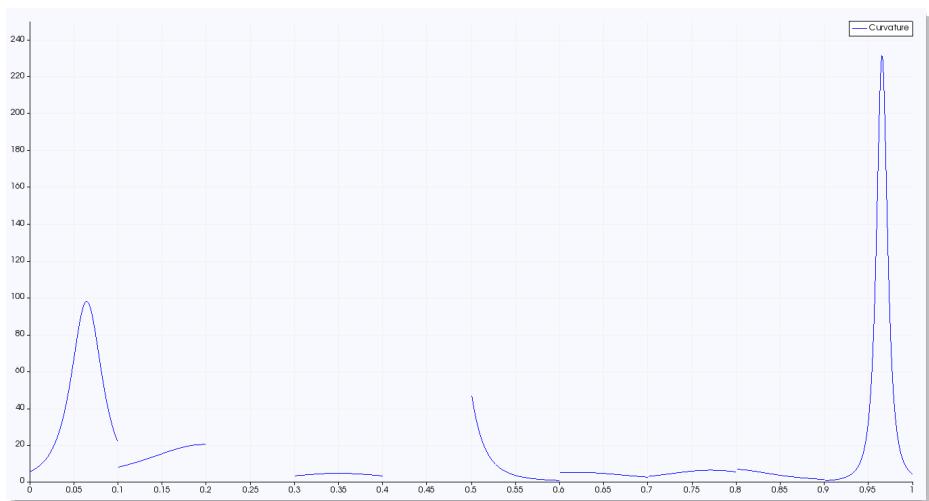
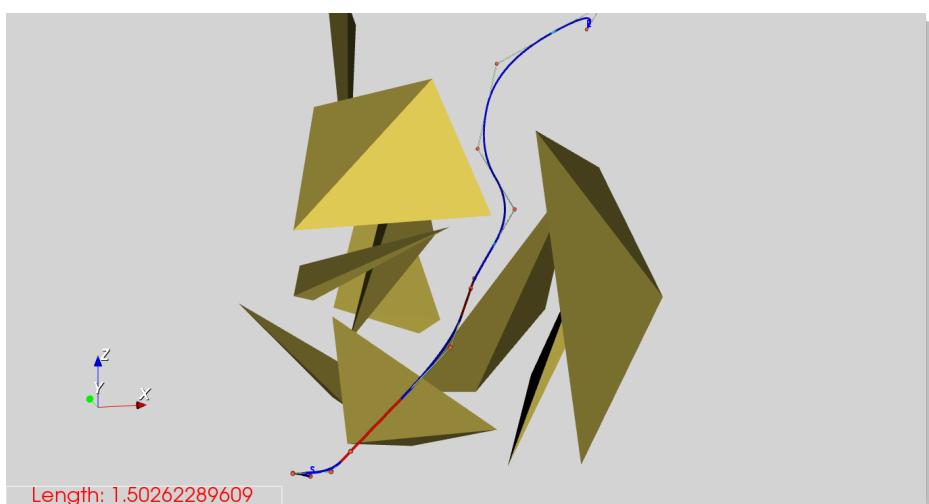
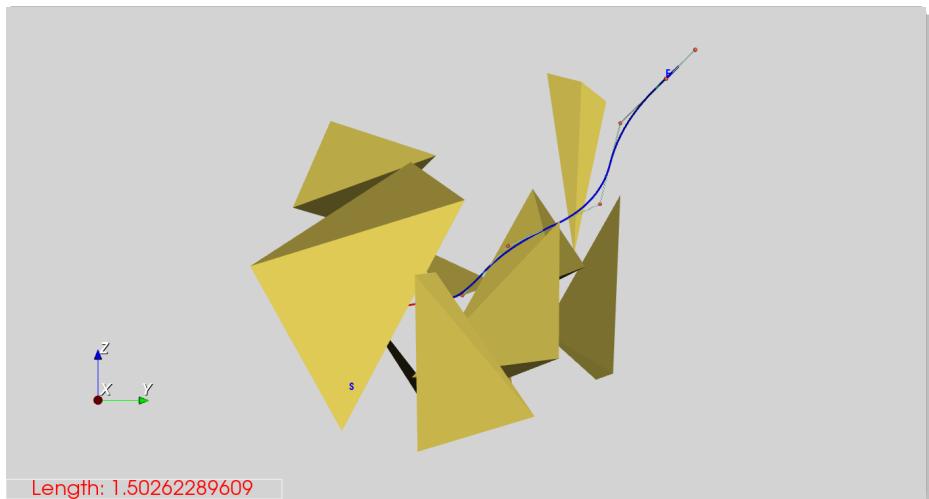


Figure 41.: Test 13; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 2; Meth. B; Post proc. X; Part. U.

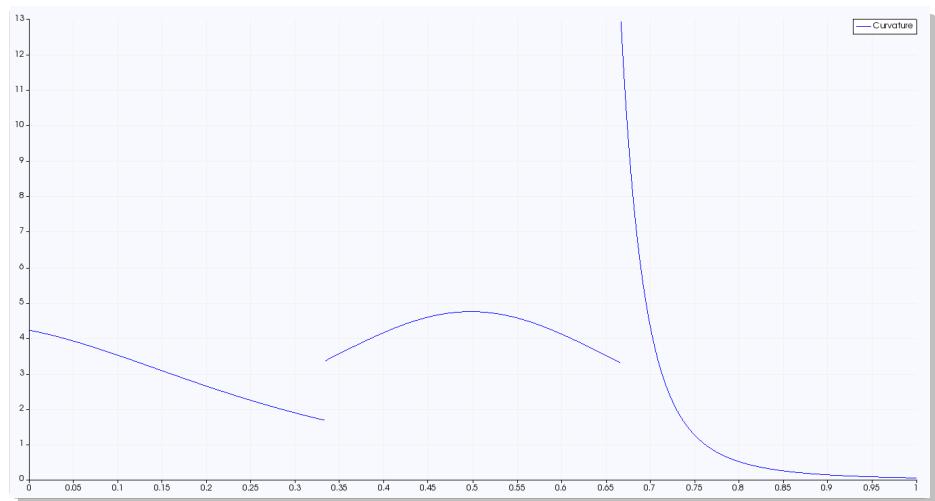
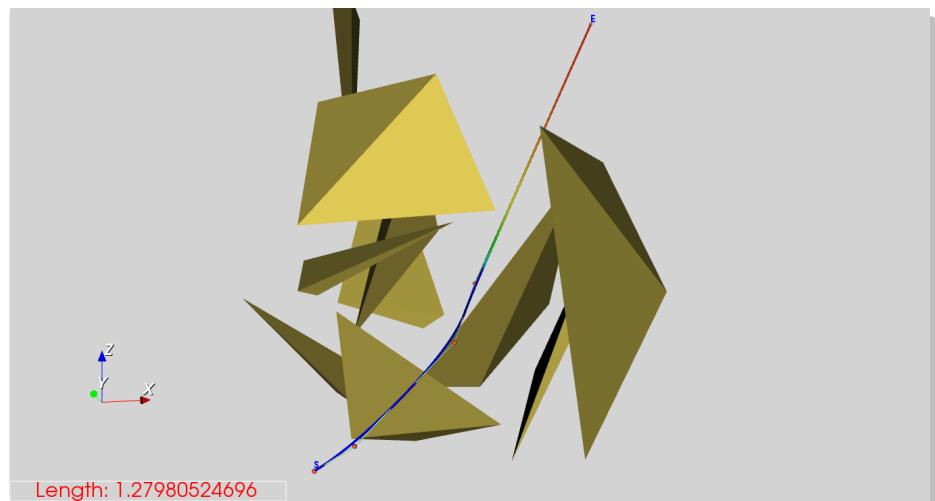
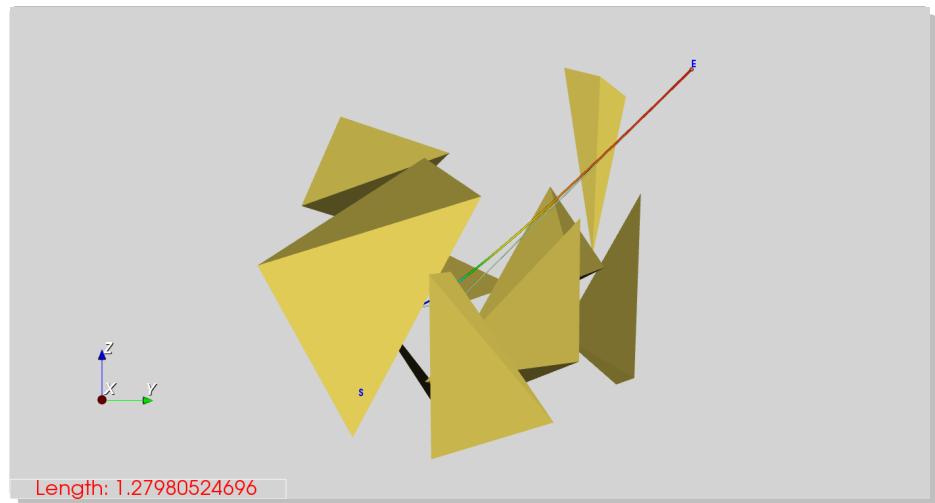


Figure 42.: Test 14; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 2; Meth. B; Post proc. ✓; Part. U.

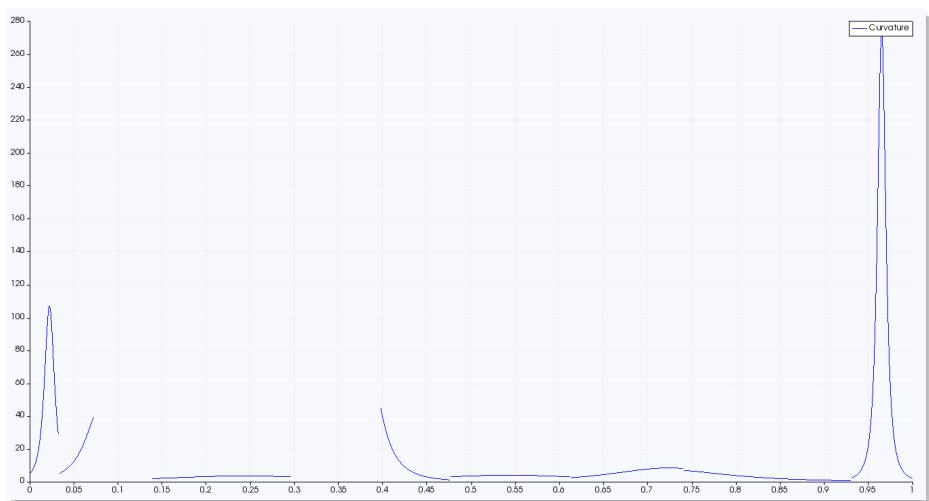
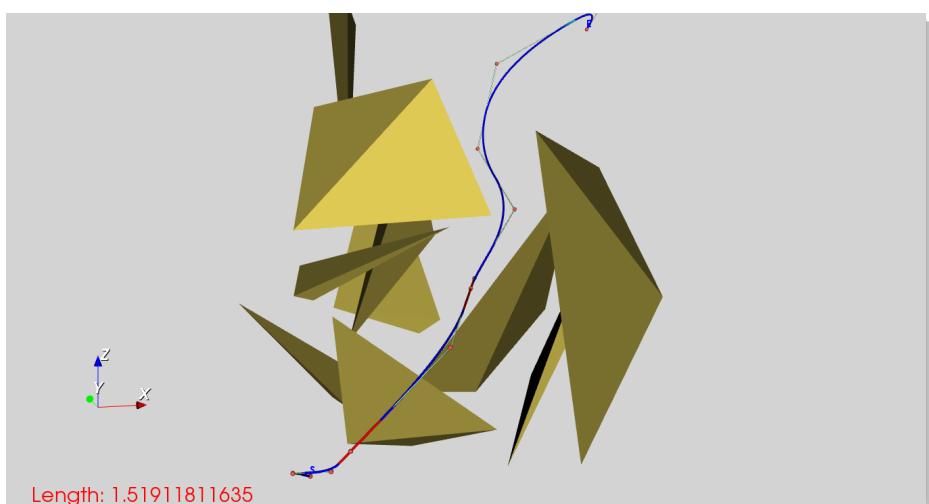
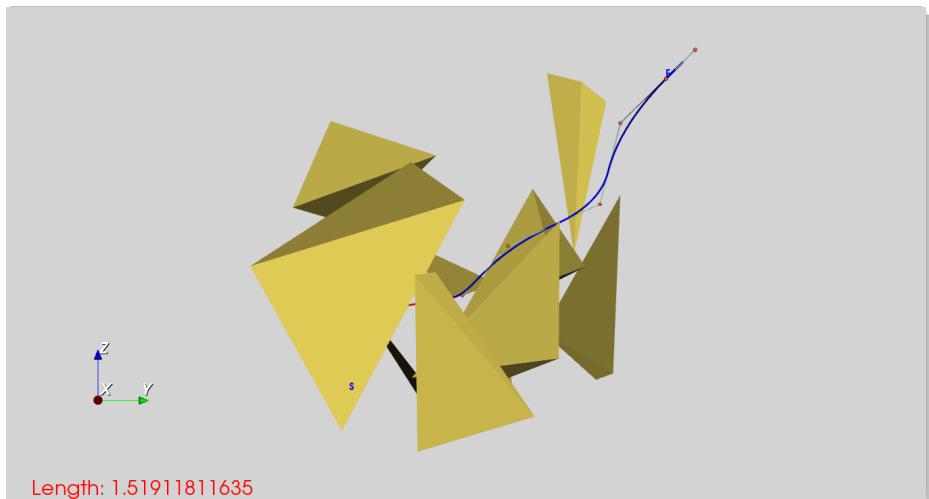


Figure 43.: Test 15; Scene 1;  $s \rightarrow e [0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 2; Meth. B; Post proc. X; Part. A.

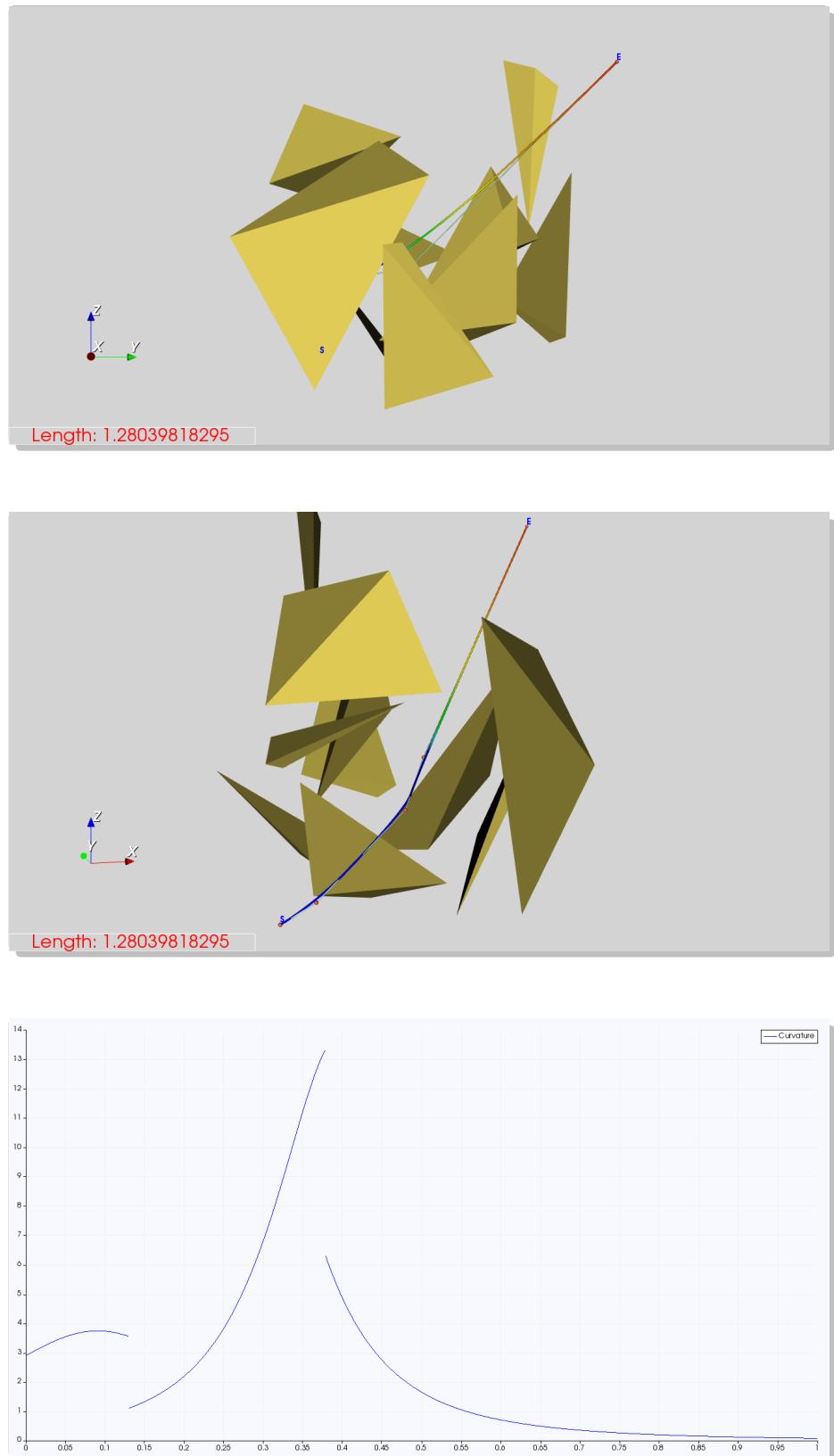


Figure 44.: Test 16; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 2; Meth. B; Post proc. ✓; Part. A.

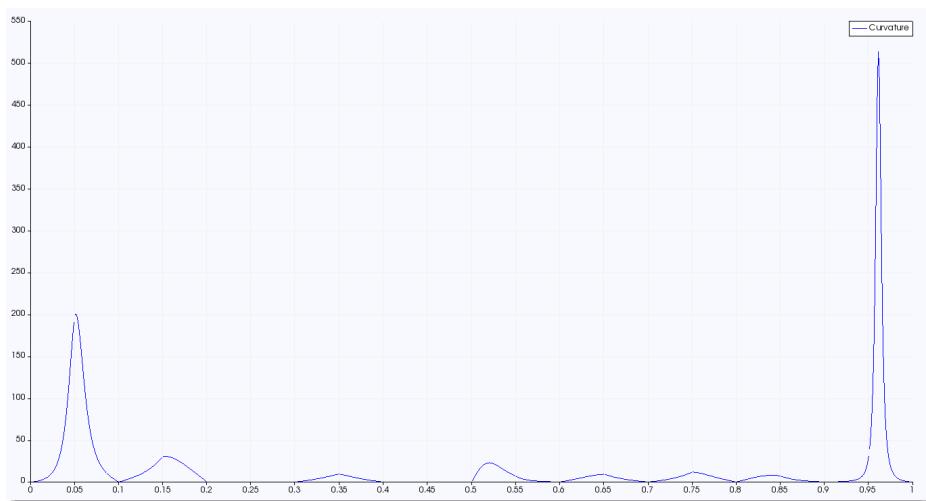
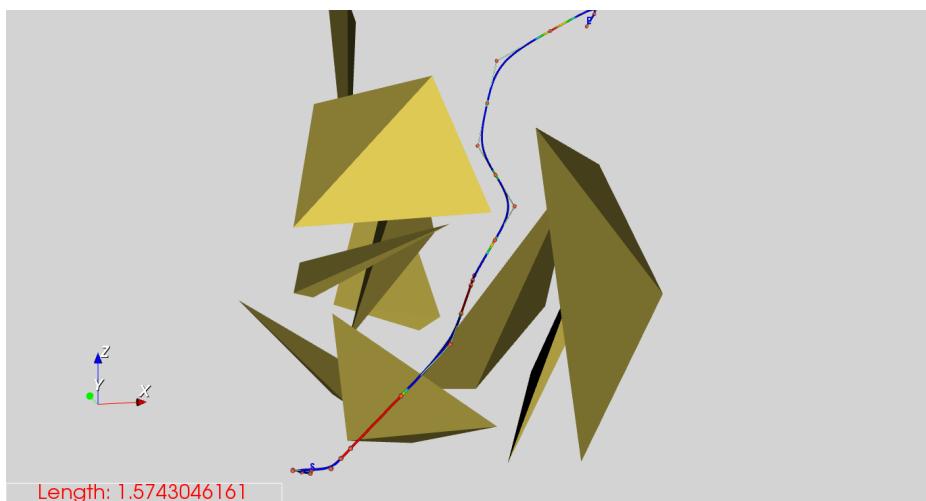
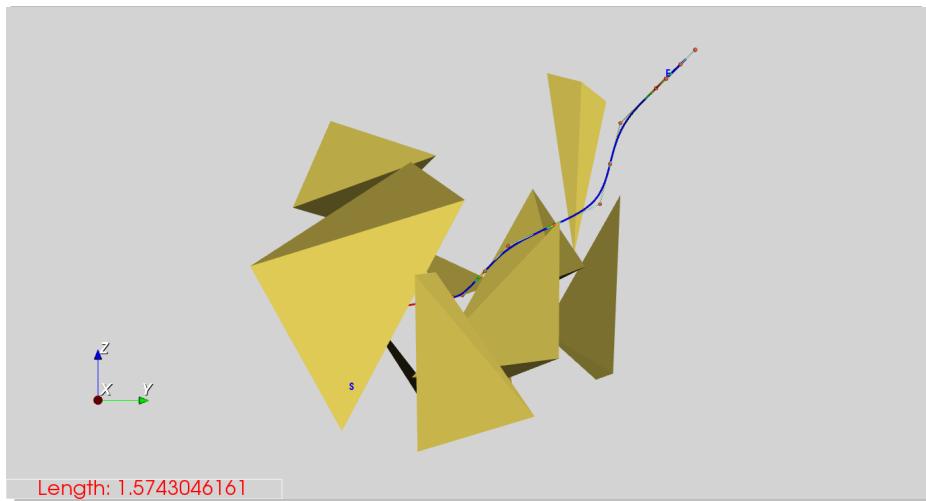


Figure 45.: Test 17; Scene 1;  $s \rightarrow e [0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 3; Meth. B; Post proc. X; Part. U.

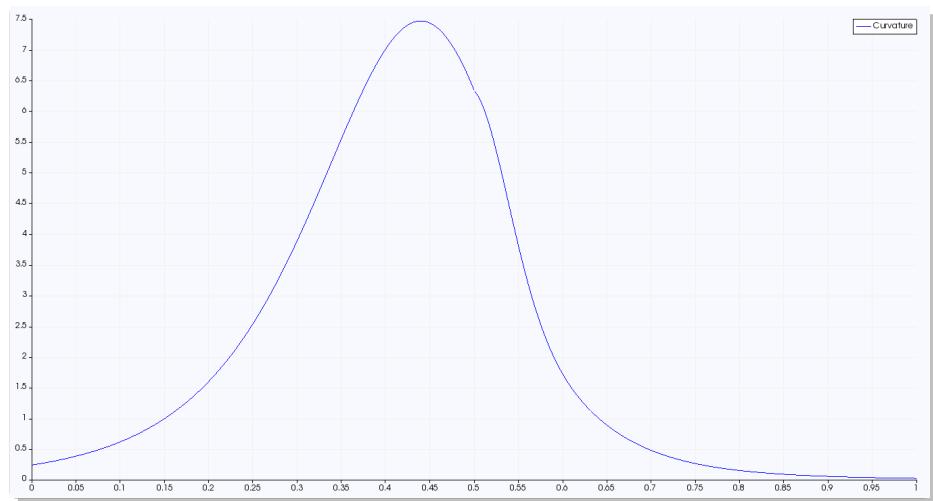
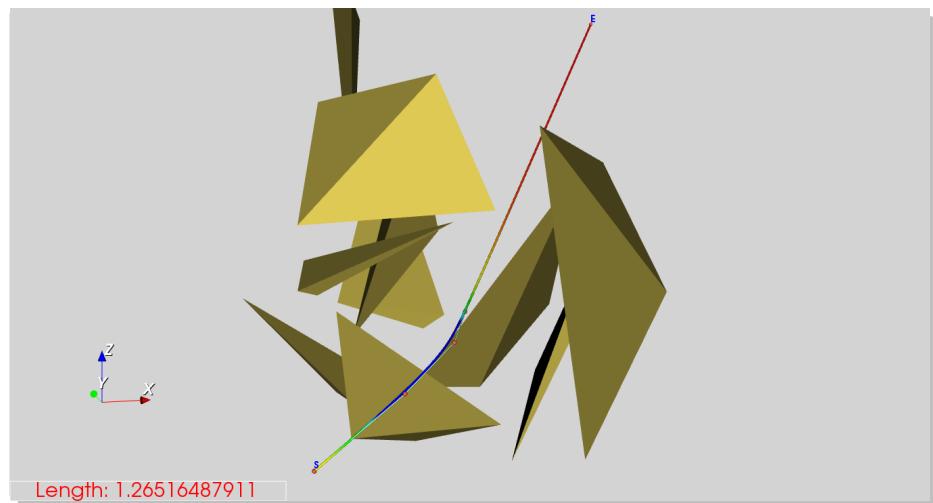
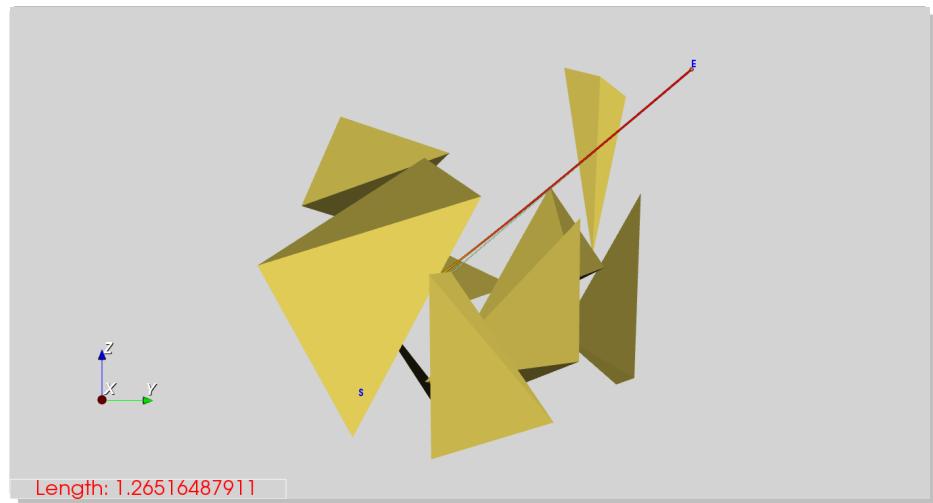


Figure 46.: Test 18; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 3; Meth. B; Post proc. ✓; Part. U.

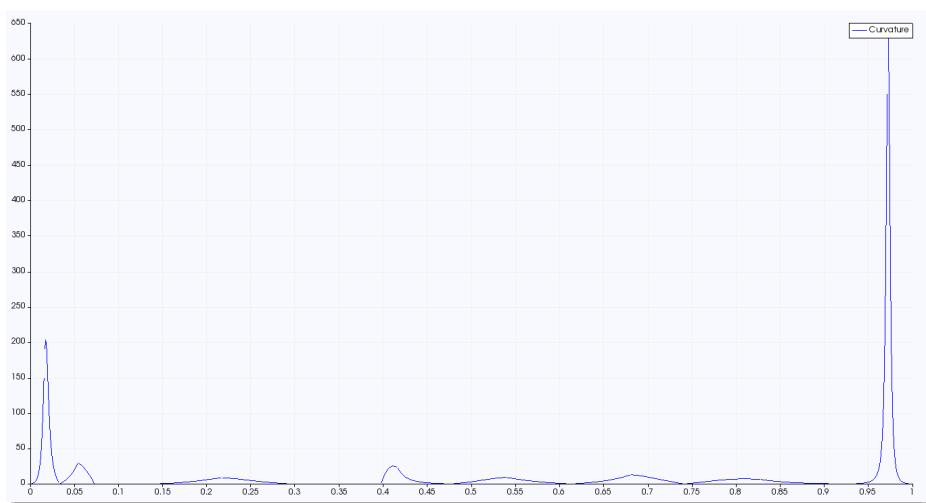
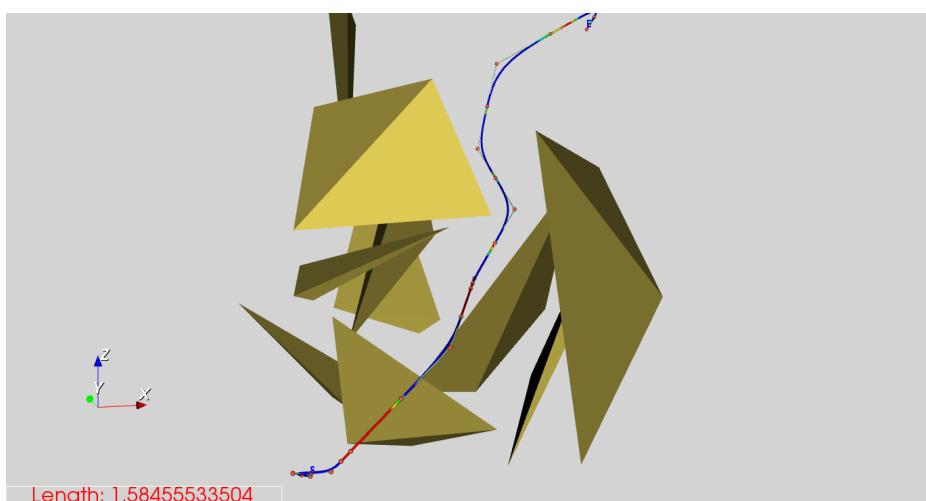
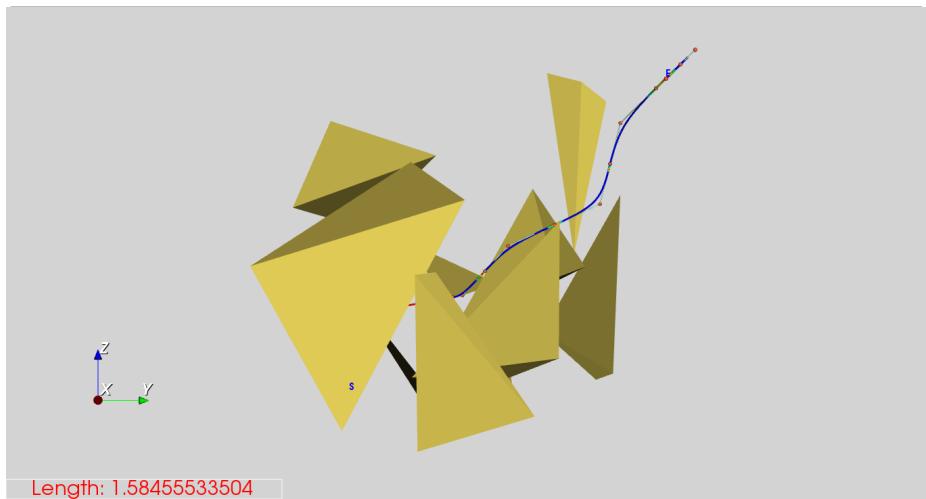


Figure 47.: Test 19; Scene 1;  $s \rightarrow e [0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 3; Meth. B; Post proc. X; Part. A.

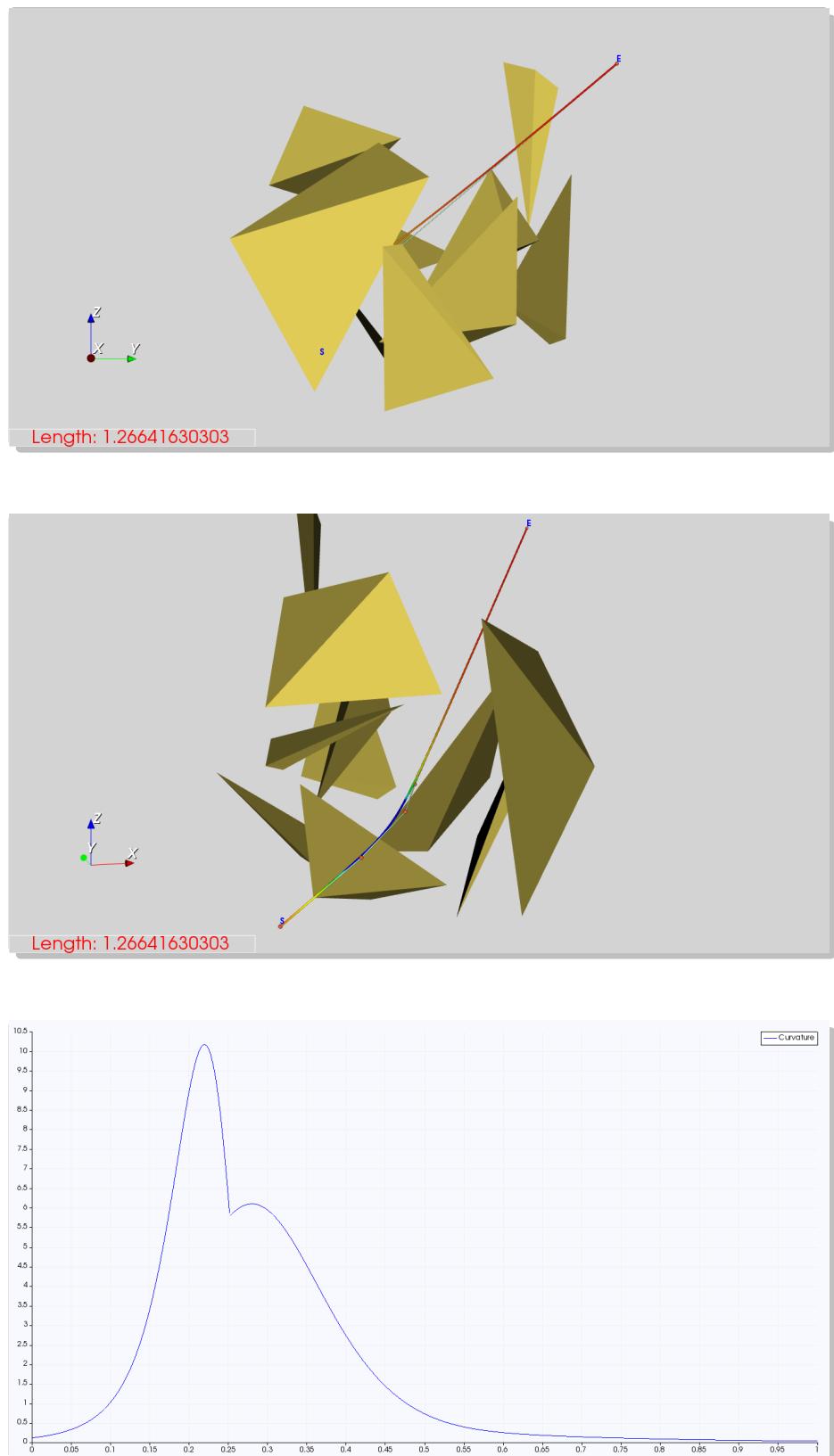


Figure 48.: Test 20; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 3; Meth. B; Post proc. ✓; Part. A.

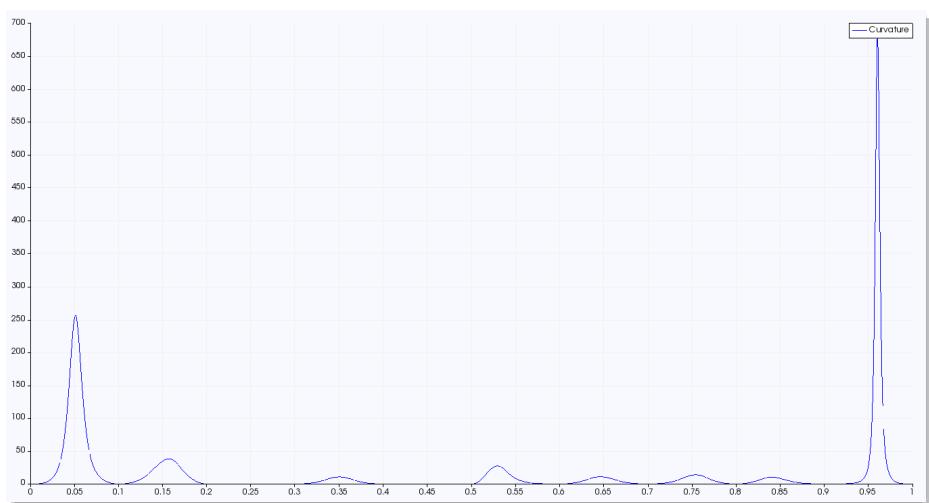
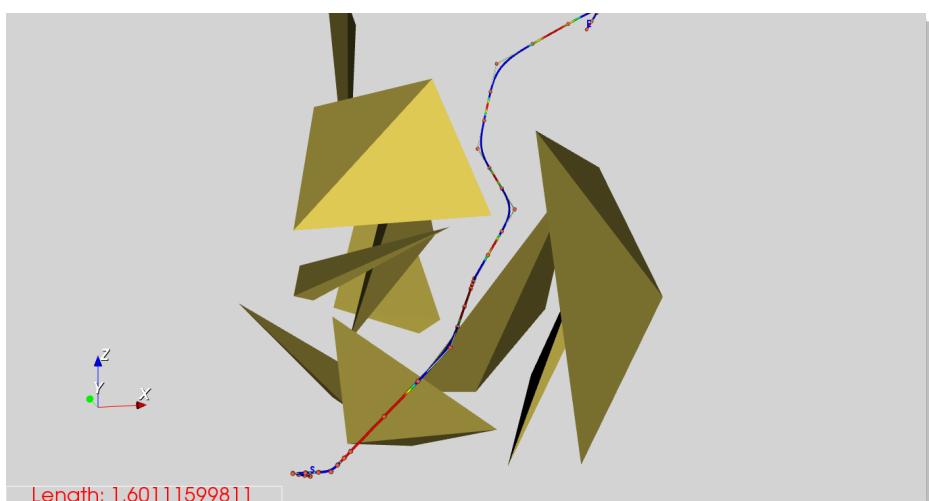
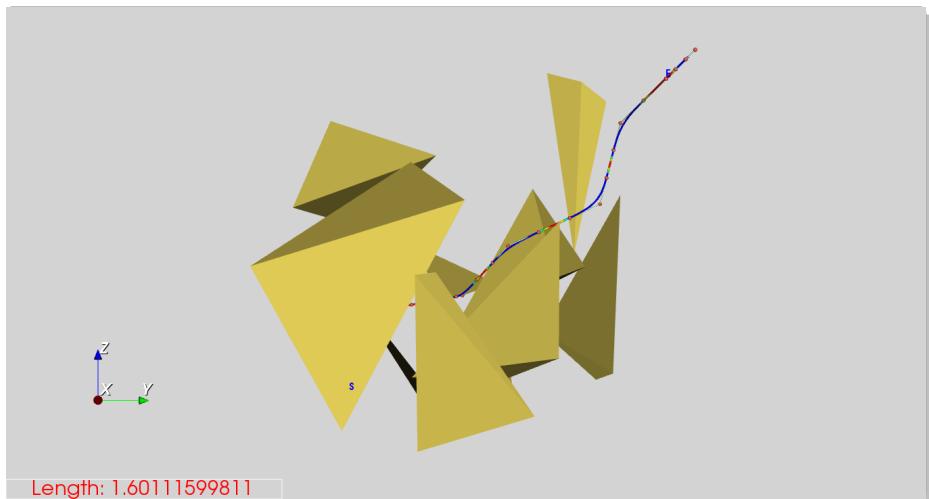


Figure 49.: Test 21; Scene 1;  $s \rightarrow e [0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 4; Meth. B; Post proc. X; Part. U.

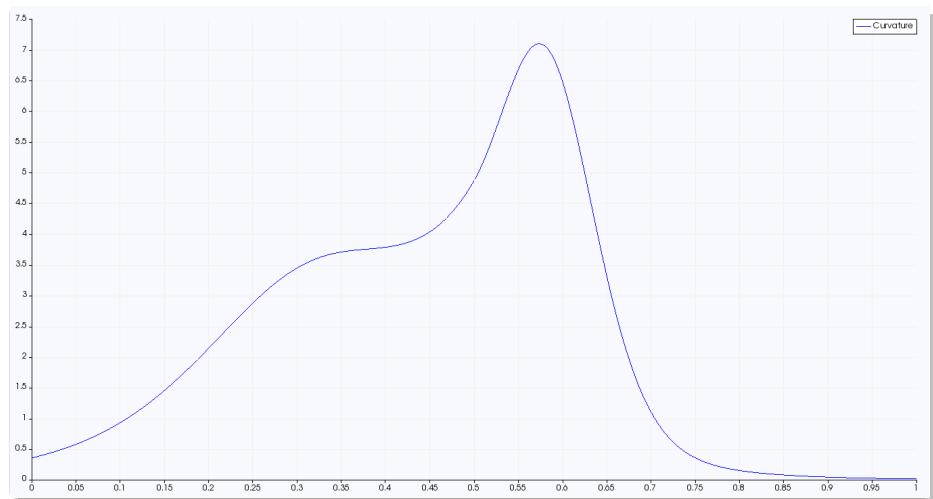
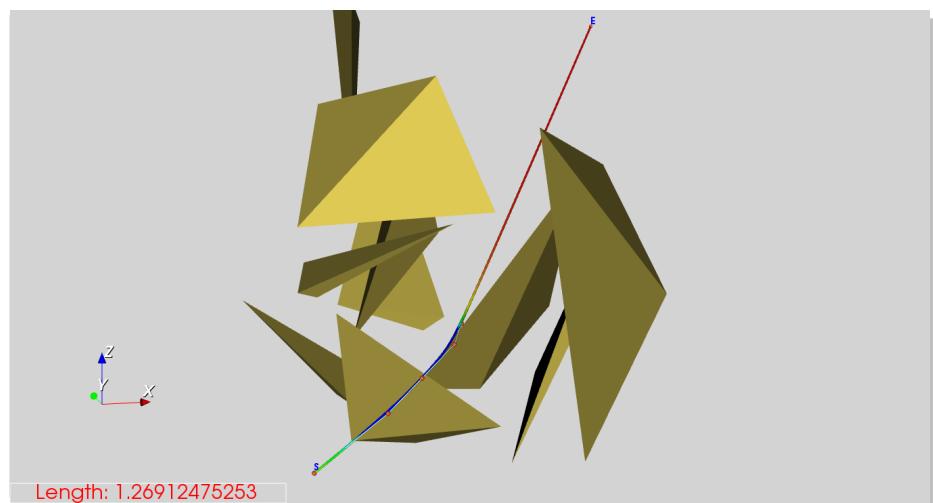
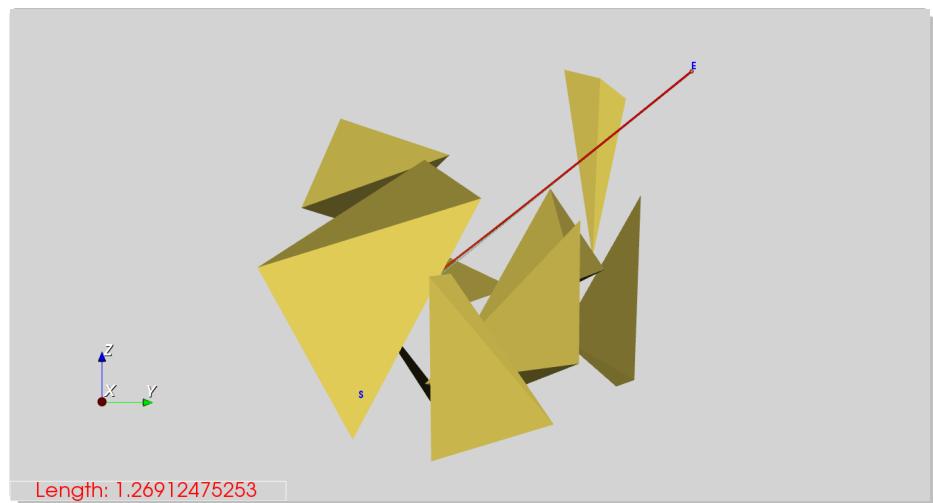


Figure 50.: Test 22; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 4; Meth. B; Post proc. ✓; Part. U.

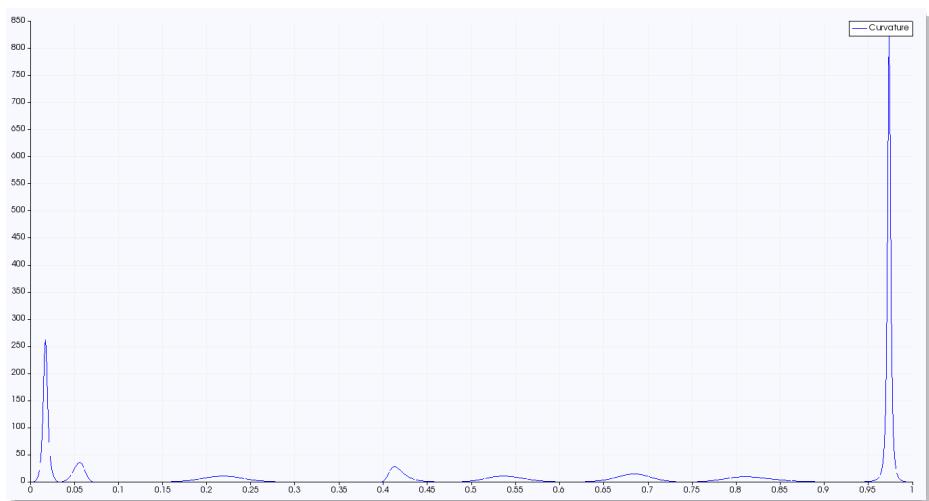
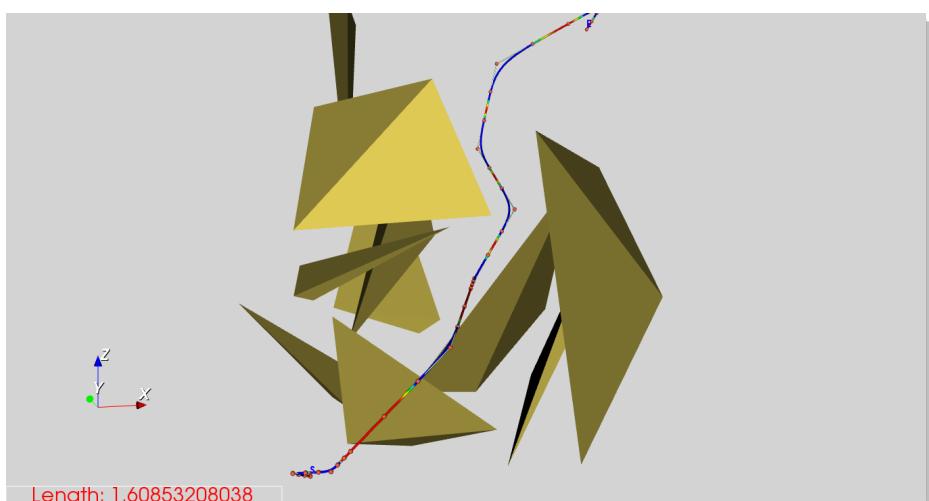
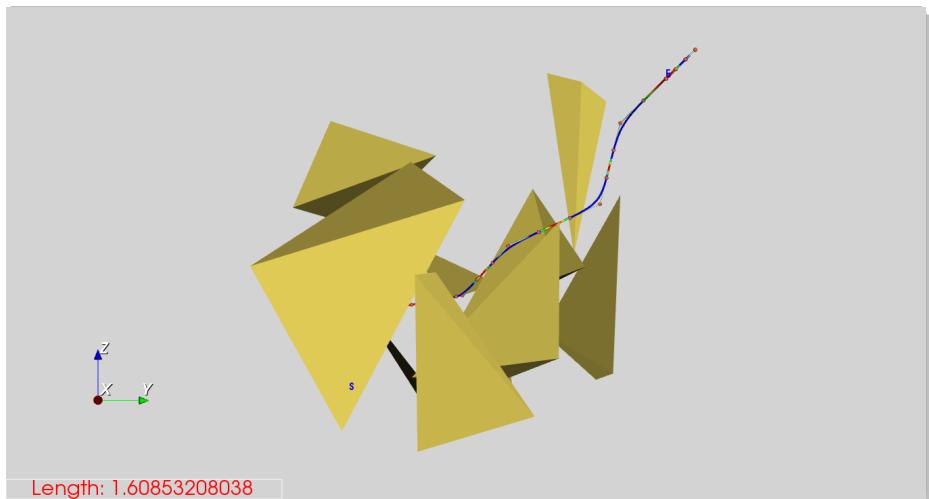


Figure 51.: Test 23; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 4; Meth. B; Post proc. X; Part. A.

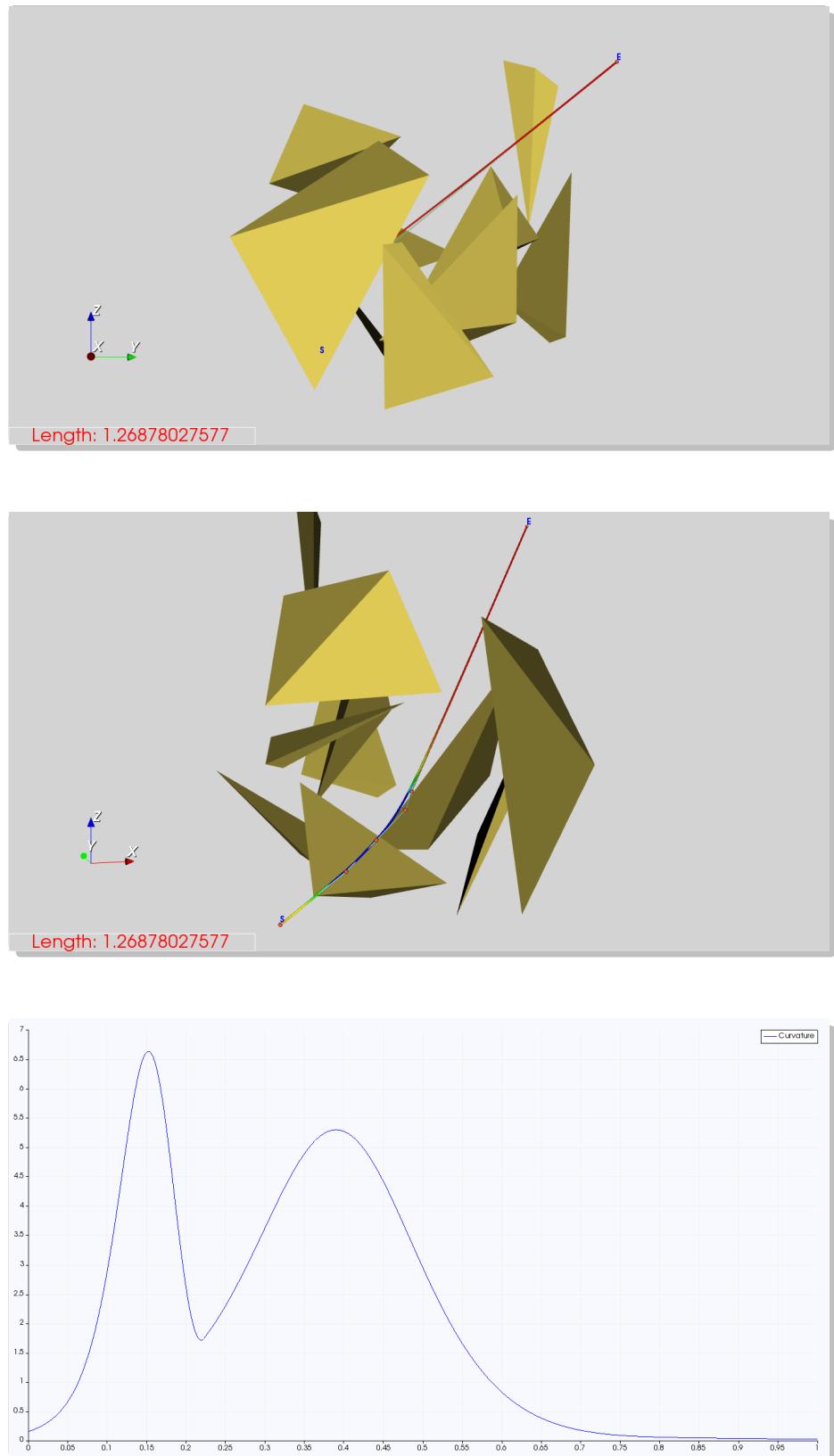


Figure 52.: Test 24; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 4; Meth. B; Post proc. ✓; Part. A.

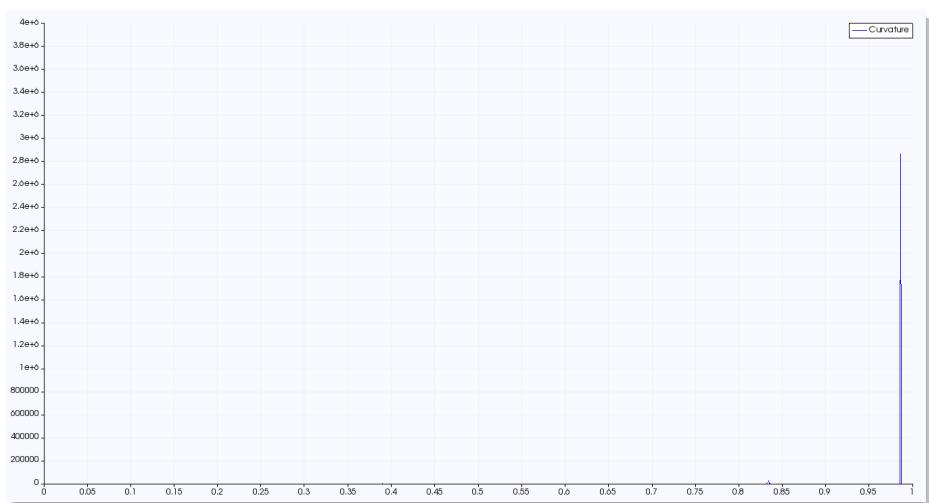
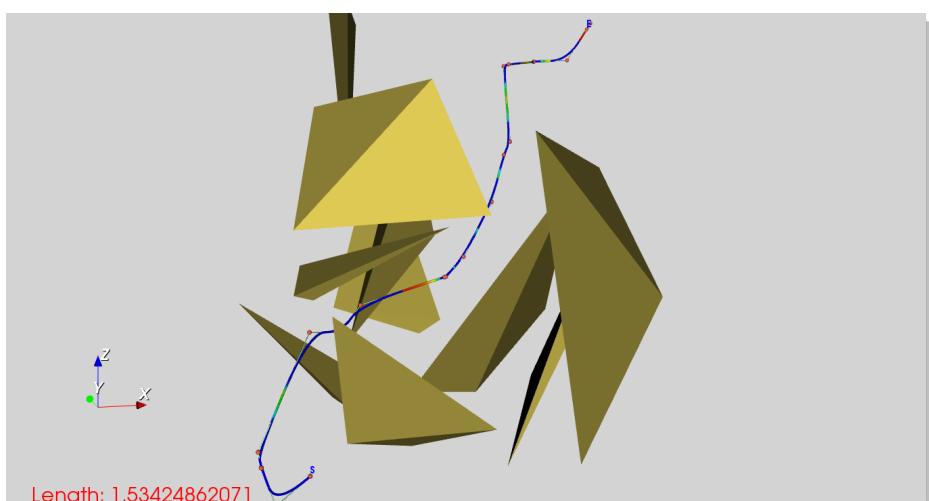
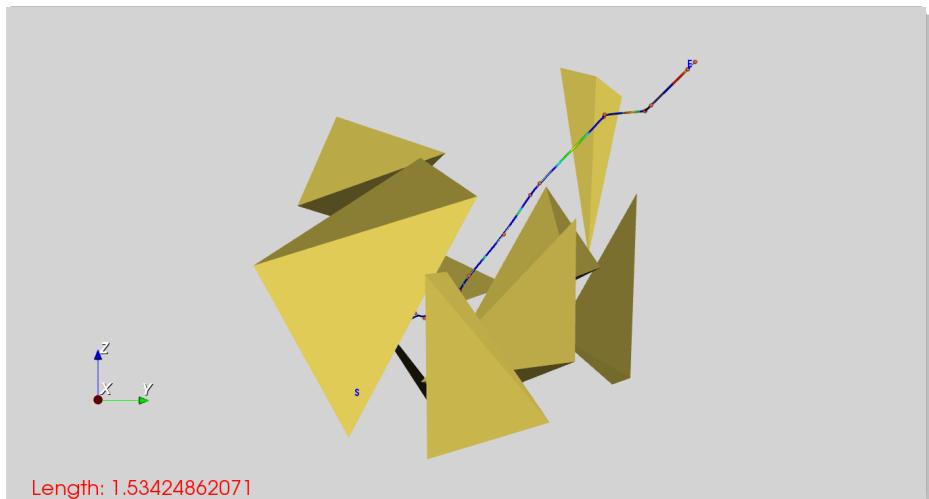


Figure 53.: Test 25; Scene 1b;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 2; Meth. B; Post proc. X; Part. U.

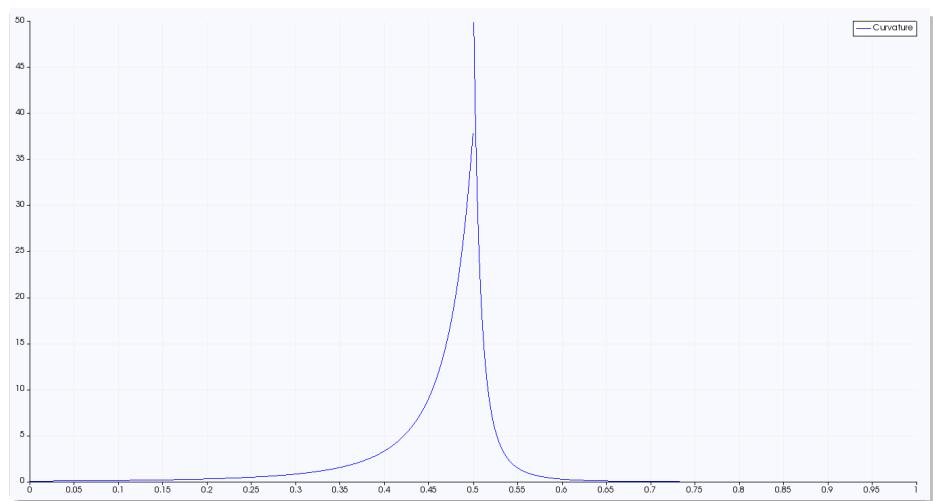
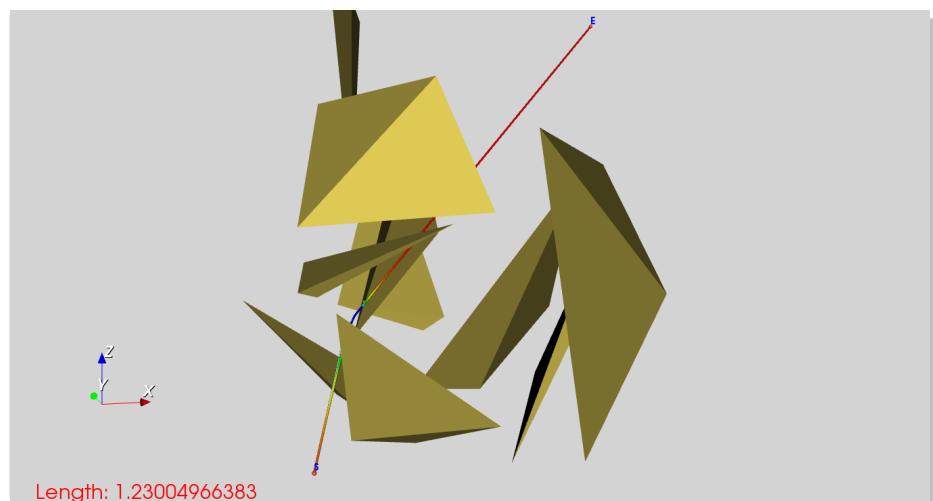
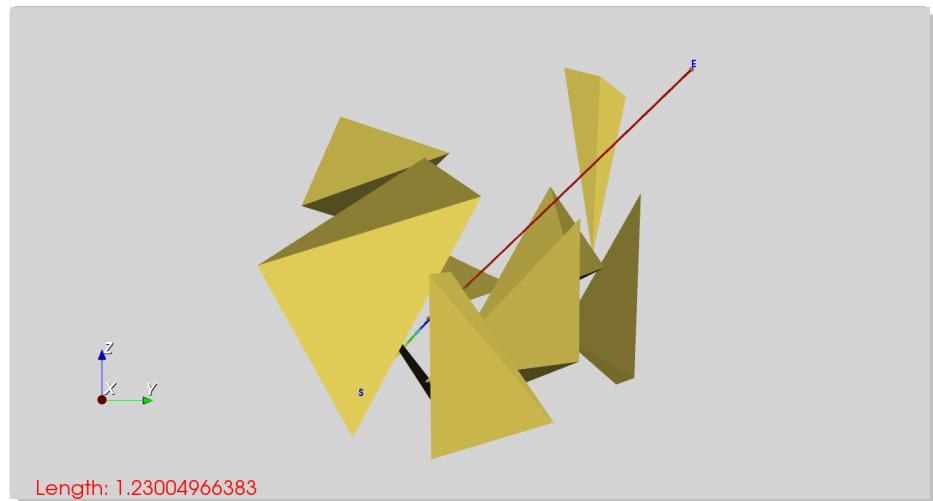


Figure 54.: Test 26; Scene 1b;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 2; Meth. B; Post proc. ✓; Part. U.

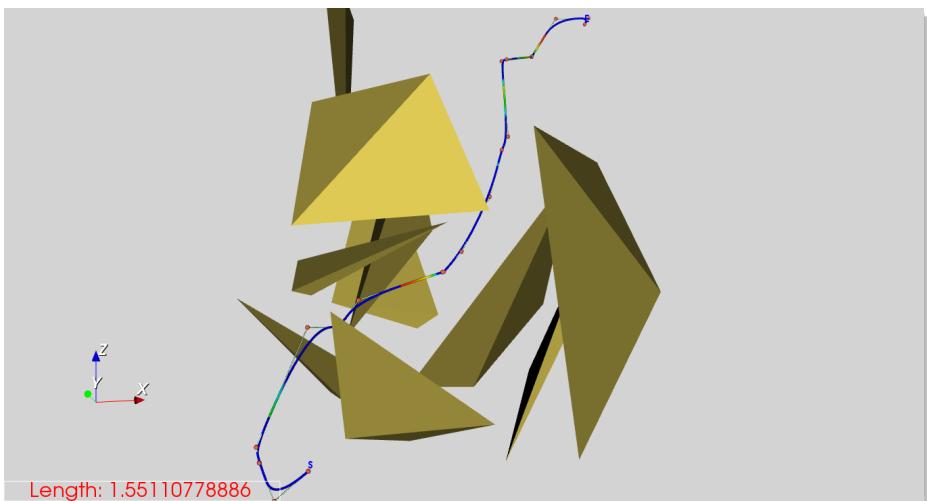
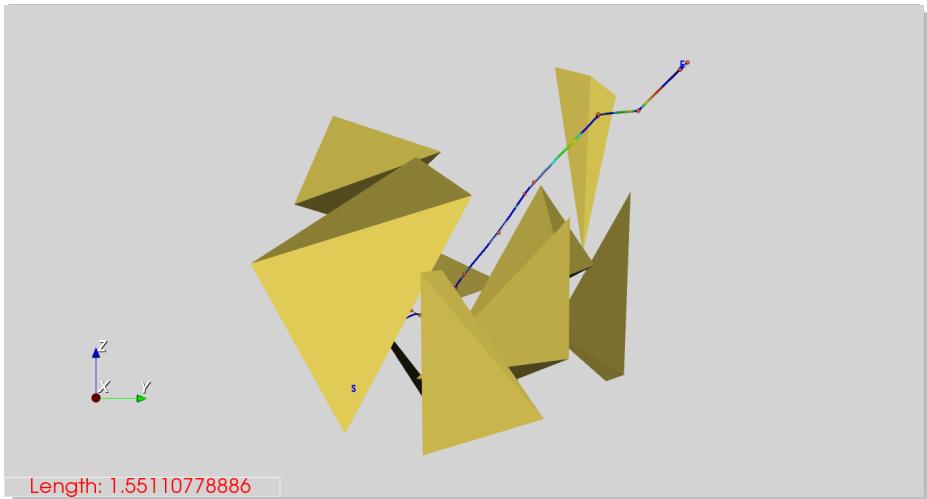


Figure 55.: Test 27; Scene 1b;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 2; Meth. B; Post proc. X; Part. A.

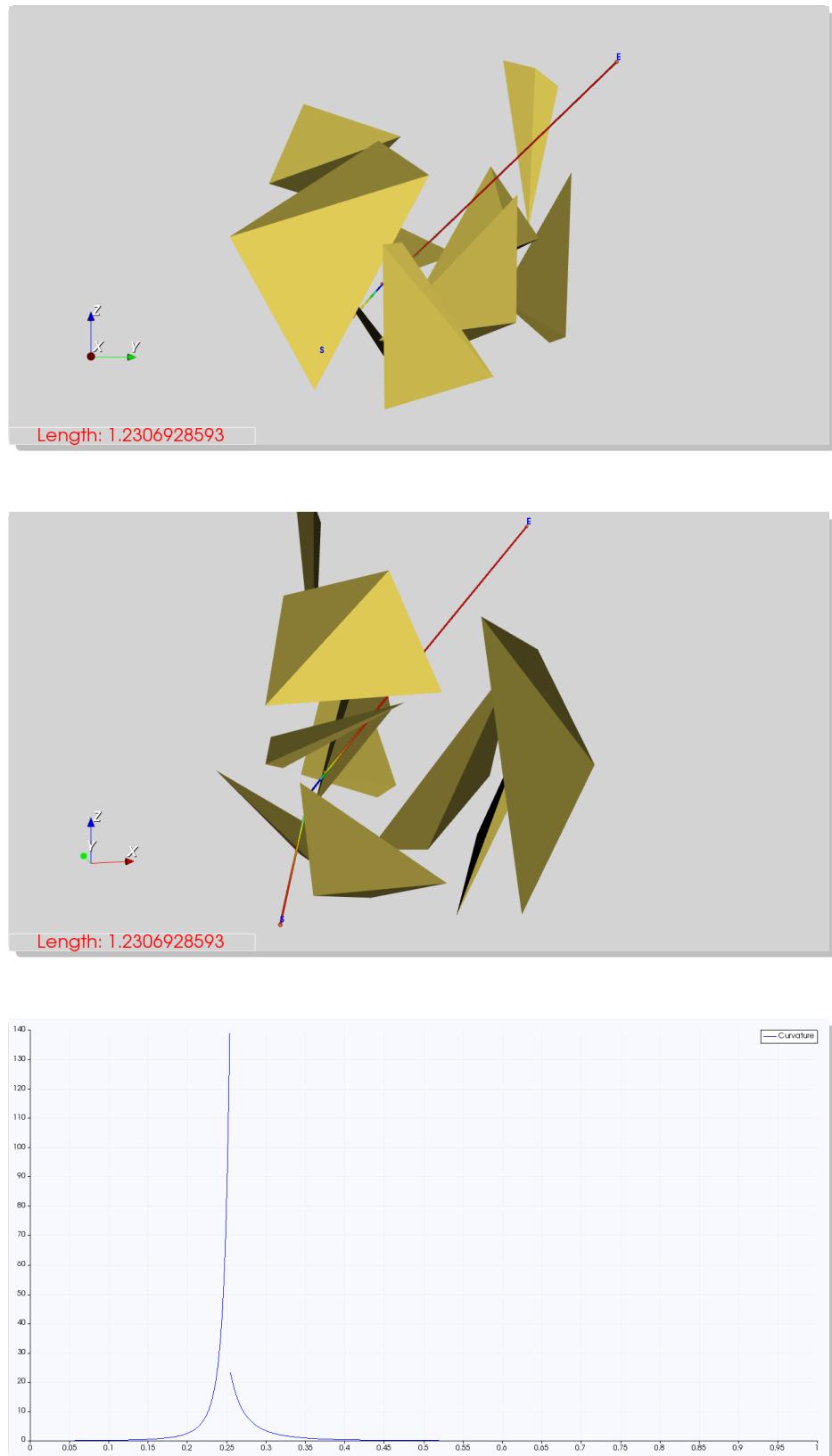


Figure 56.: Test 28; Scene 1b;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 2; Meth. B; Post proc. ✓; Part. A.

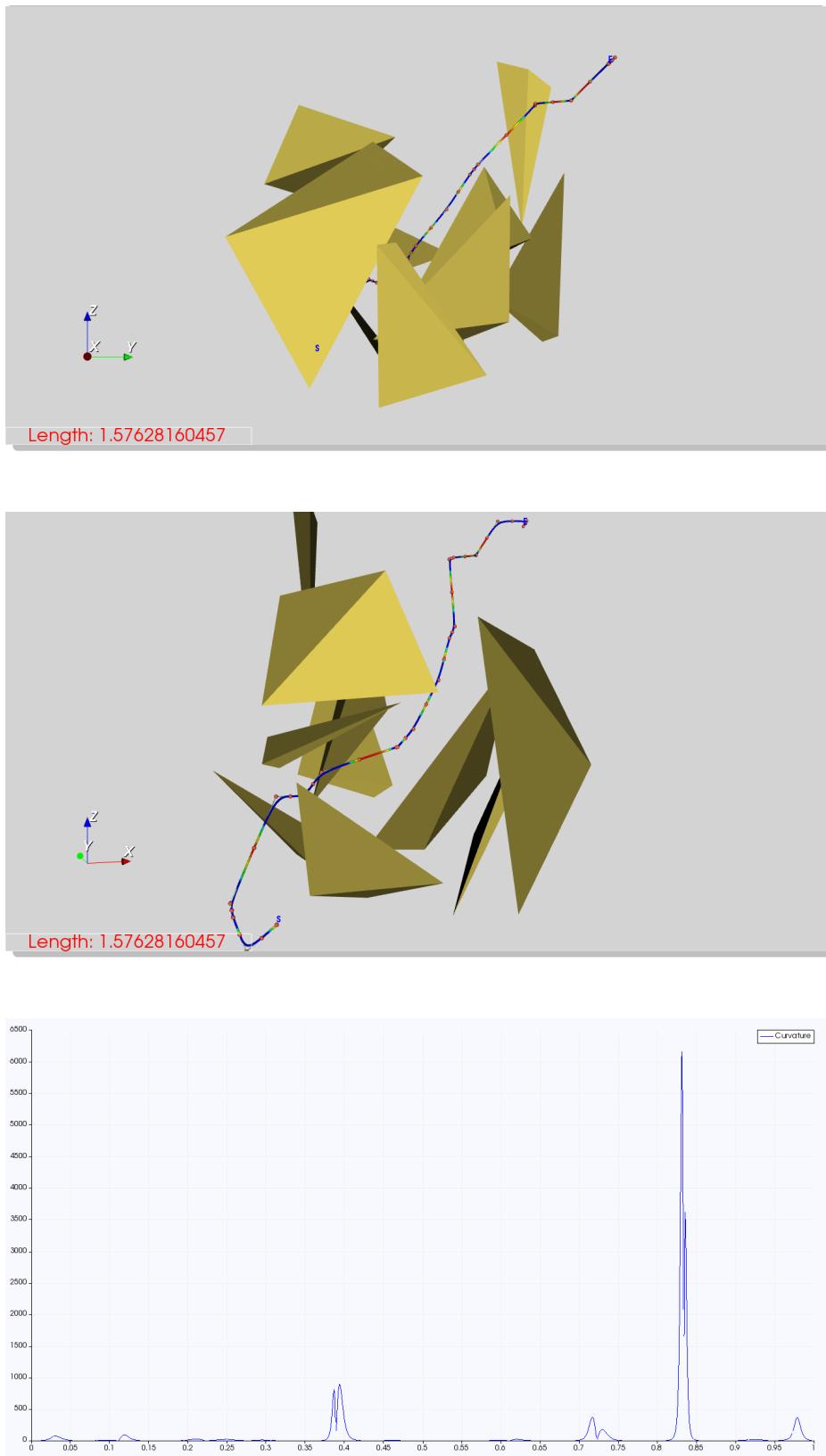


Figure 57.: Test 29; Scene 1b;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 3; Meth. B; Post proc. X; Part. U.

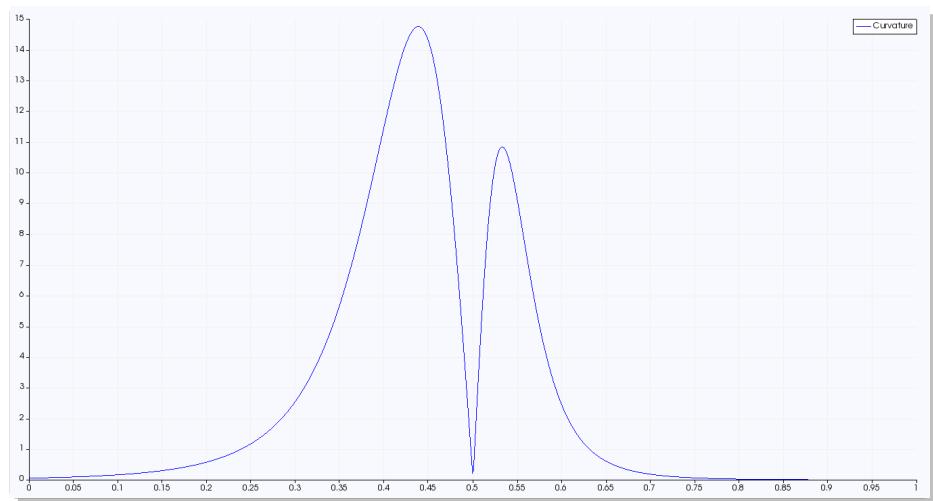
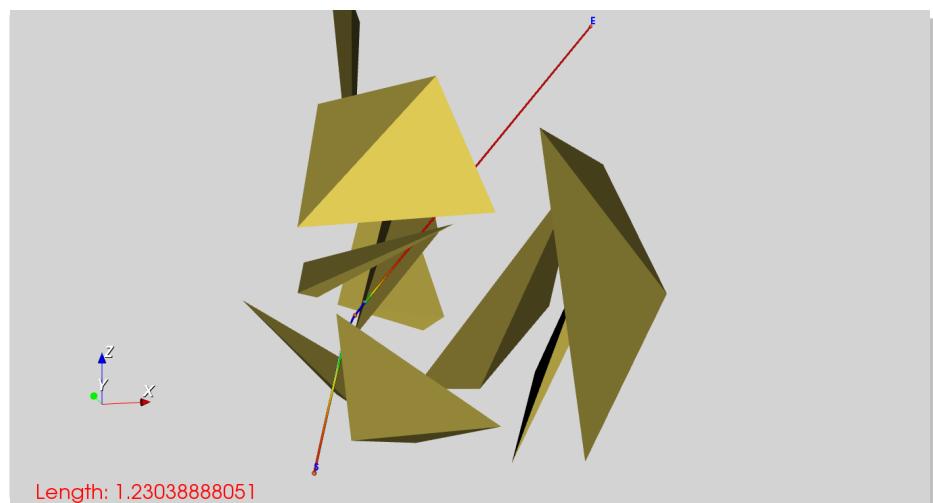
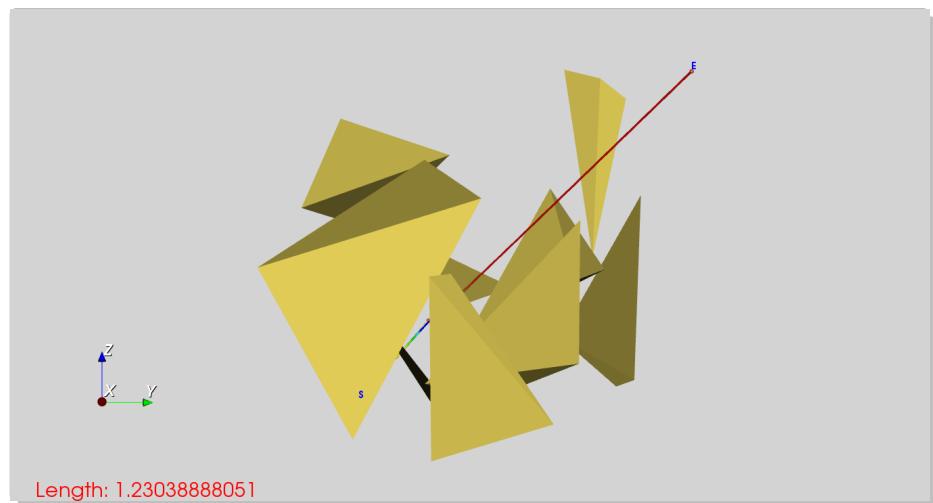


Figure 58.: Test 30; Scene 1b;  $s \rightarrow e [0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 3; Meth. B; Post proc. ✓; Part. U.

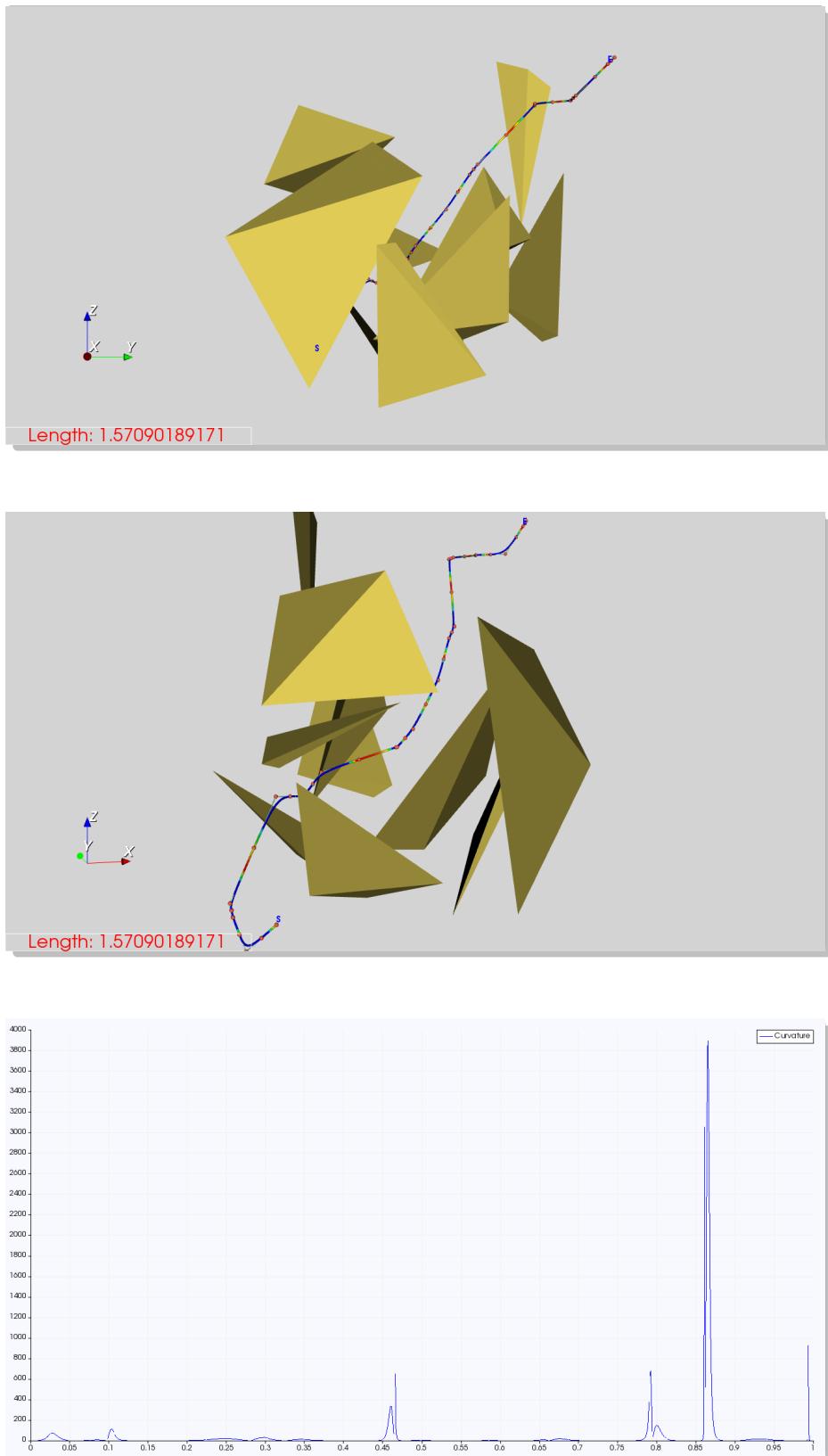


Figure 59.: Test 31; Scene 1b;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 3; Meth. B; Post proc. X; Part. A.

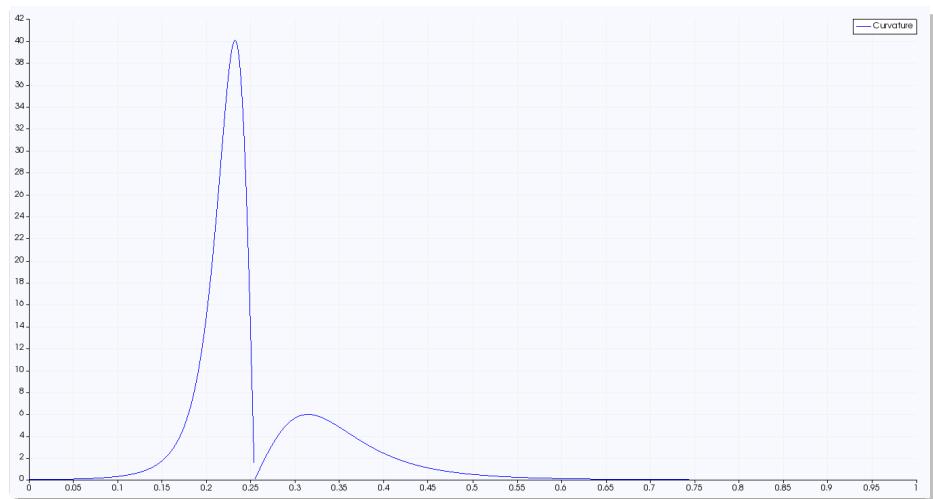
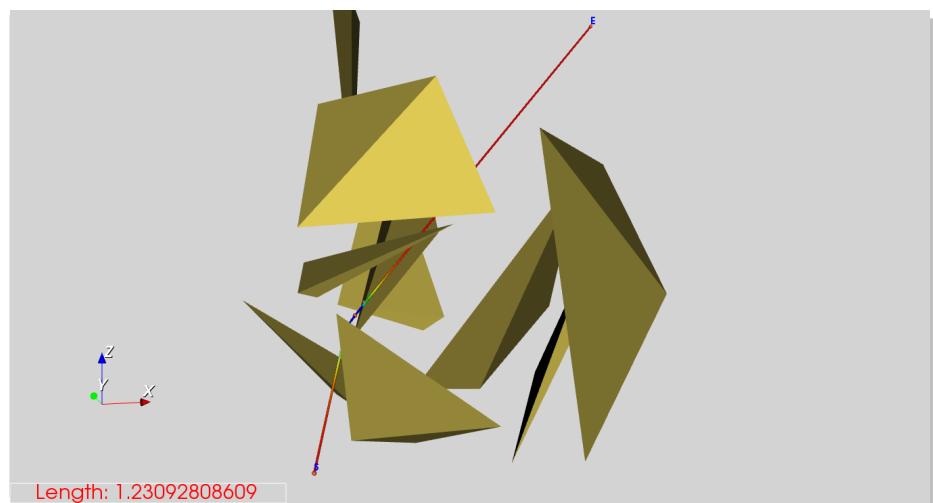
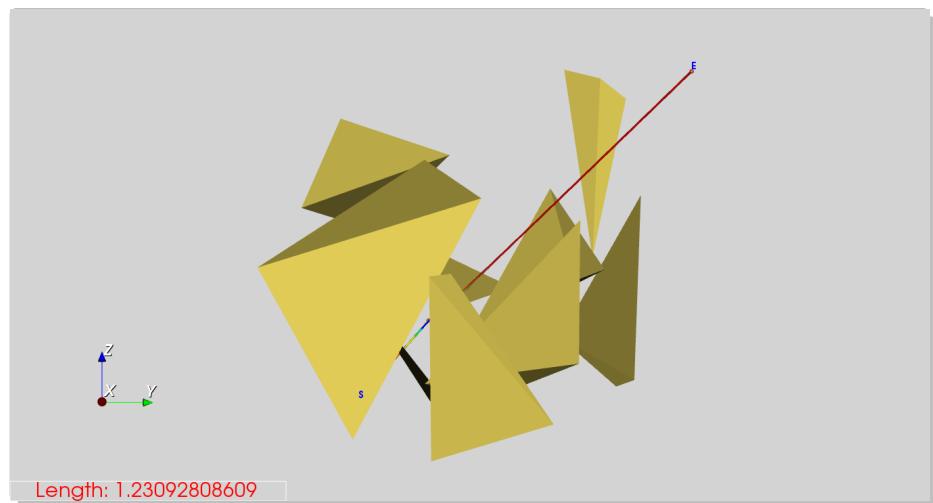


Figure 6o.: Test 32; Scene 1b;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 3; Meth. B; Post proc. ✓; Part. A.

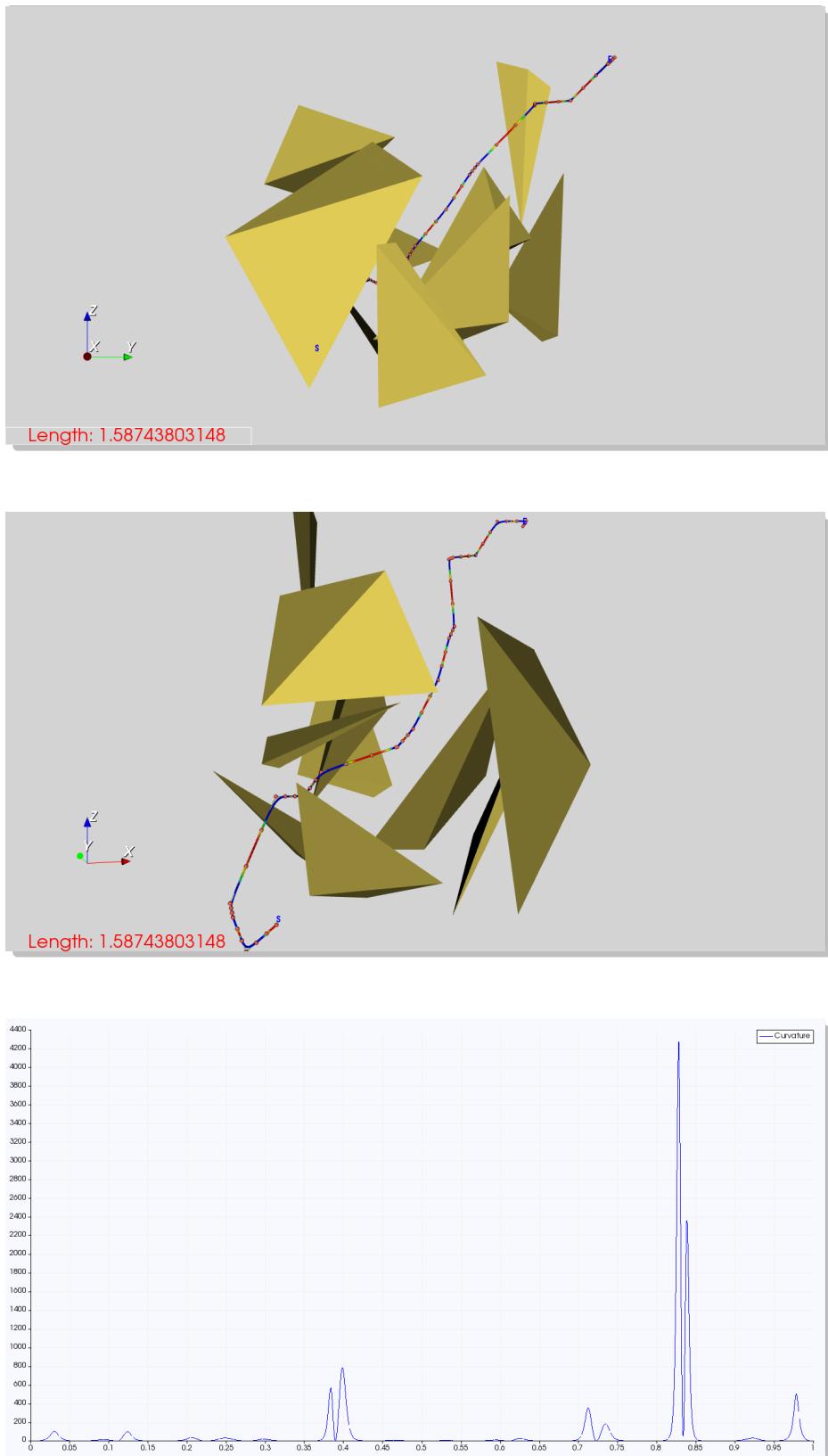


Figure 61.: Test 33; Scene 1b;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 4; Meth. B; Post proc. X; Part. U.

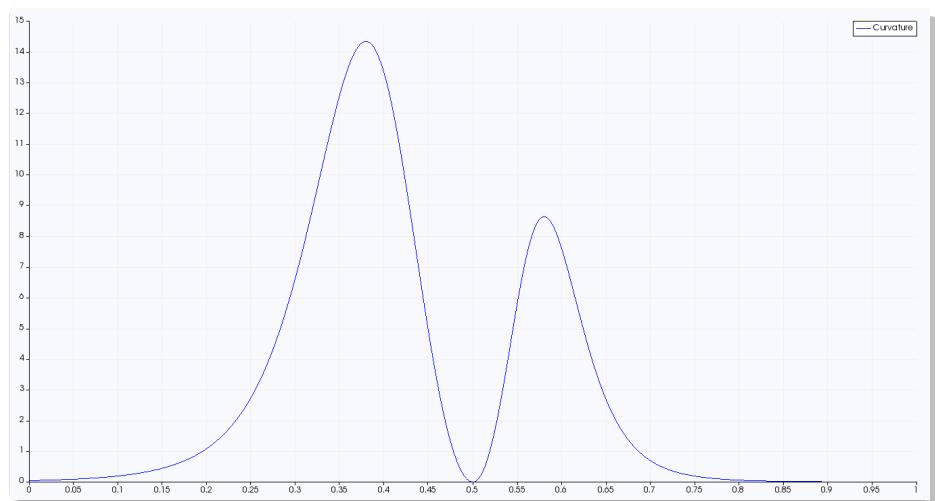
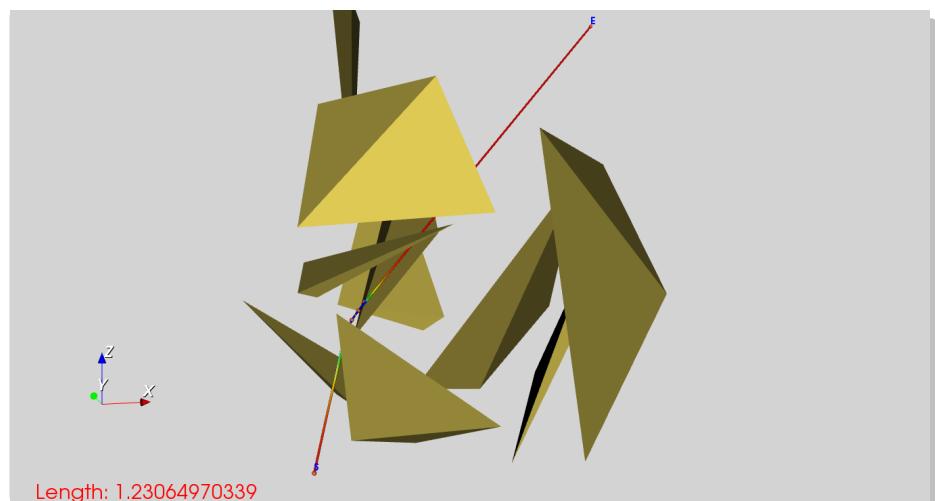
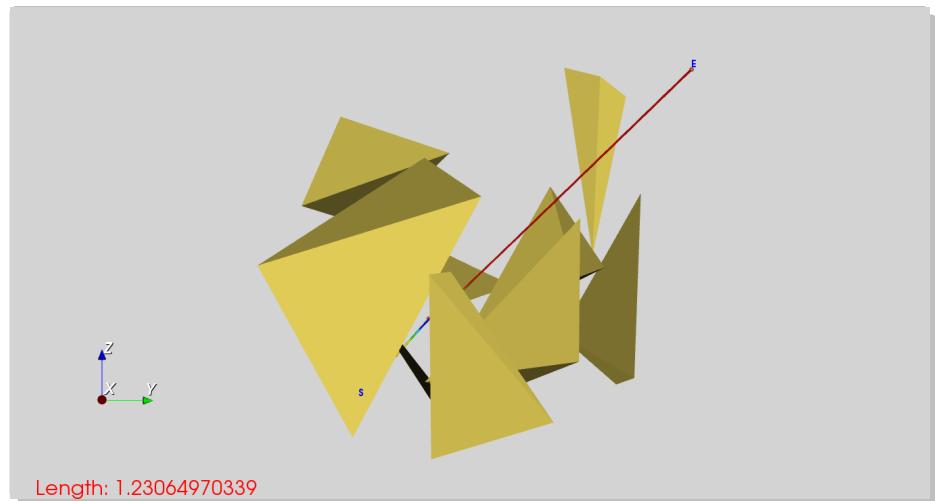


Figure 62.: Test 34; Scene 1b;  $s \rightarrow e$   $[0.2,0.2,0.2] \rightarrow [0.9,0.9,0.9]$ ; Deg. 4; Meth. B; Post proc. ✓; Part. U.

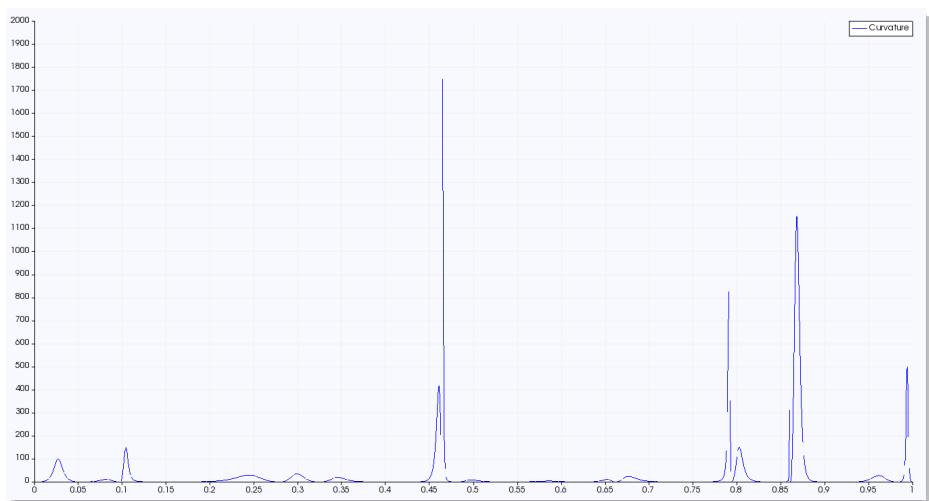
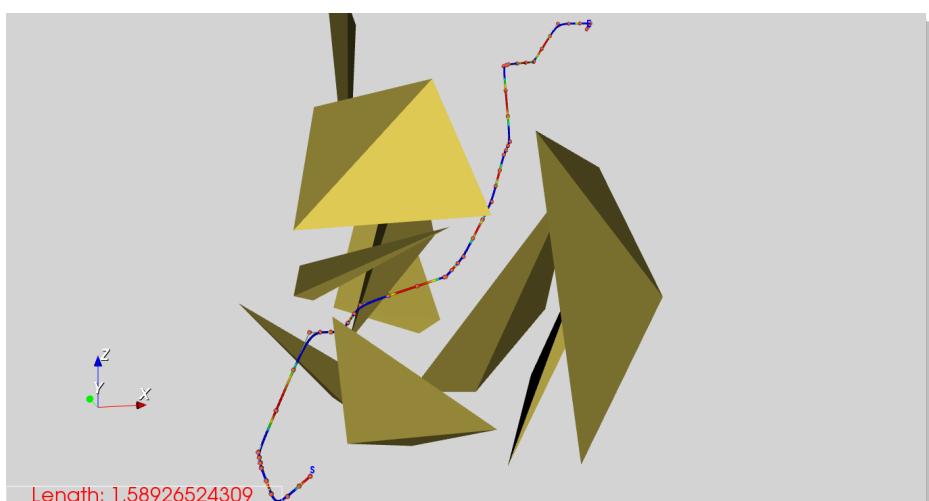
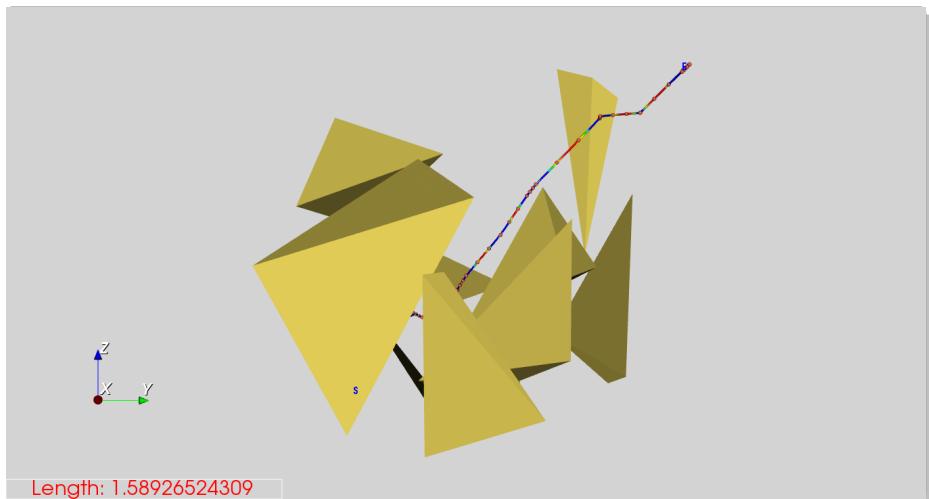


Figure 63.: Test 35; Scene 1b;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 4; Meth. B; Post proc.  $\chi$ ; Part. A.

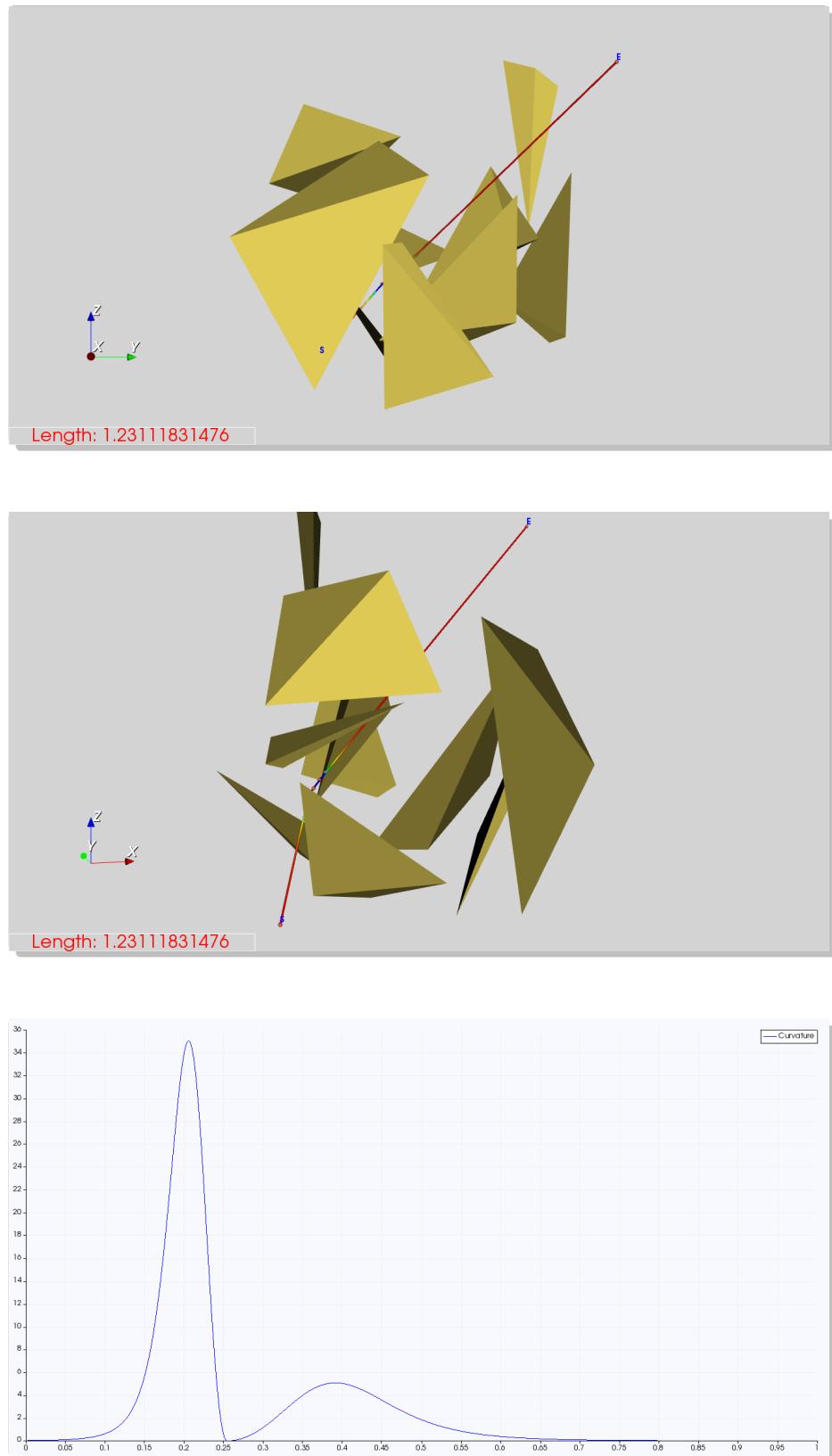


Figure 64.: Test 36; Scene 1b;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 4; Meth. B; Post proc. ✓; Part. A.

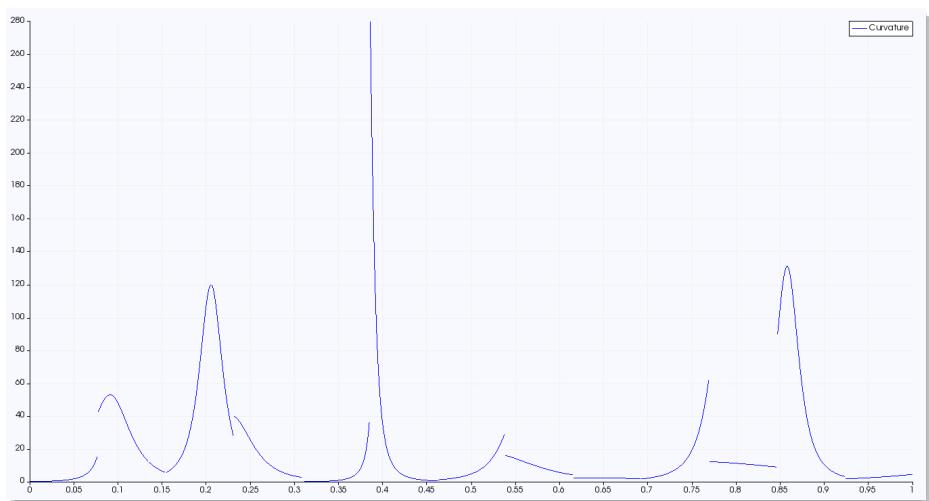


Figure 65.: Test 37; Scene 2;  $s \rightarrow e$   $[0.5,0.5,0.5] \rightarrow [0.5,0.5,0.95]$ ; Deg. 2; Meth. B; Post proc. X; Part. U.

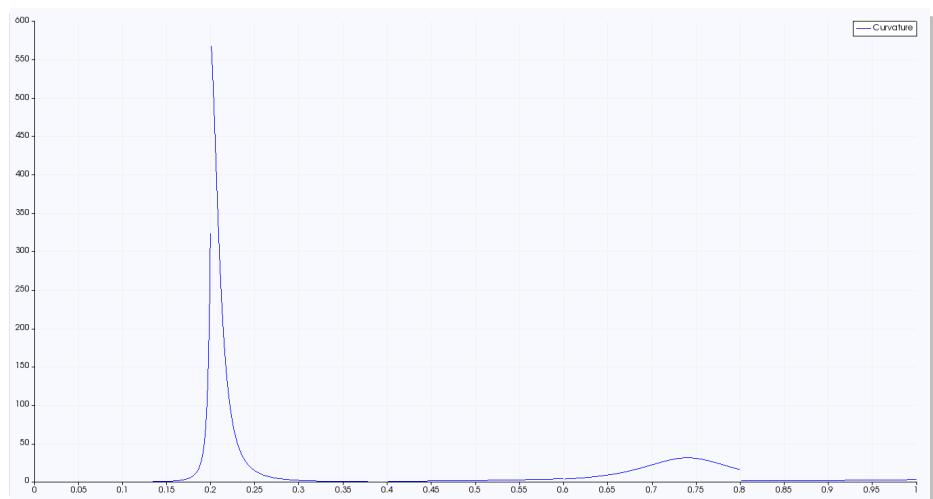
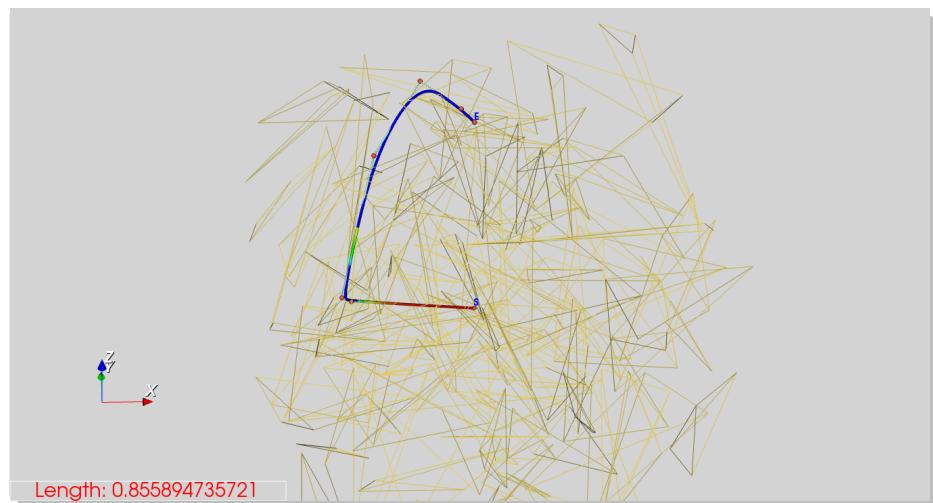
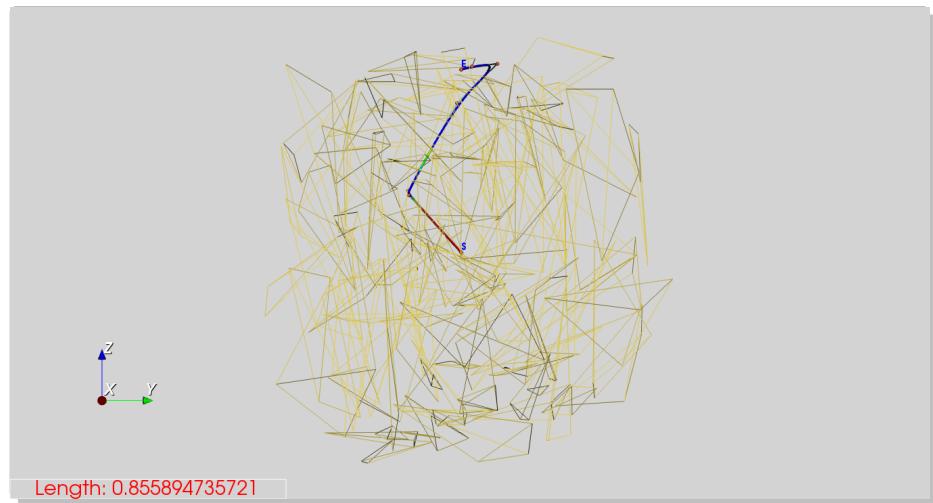


Figure 66.: Test 38; Scene 2;  $s \rightarrow e$   $[0.5, 0.5, 0.5] \rightarrow [0.5, 0.5, 0.95]$ ; Deg. 2; Meth. B; Post proc. ✓; Part. U.

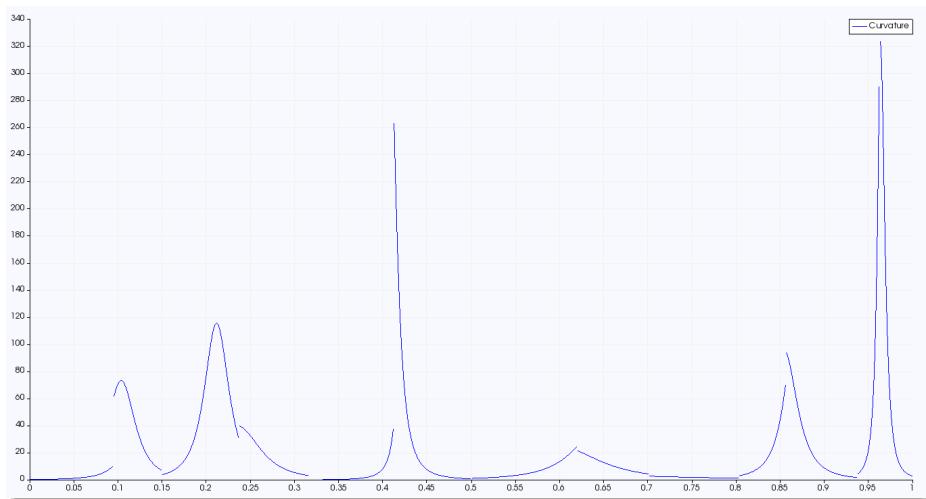
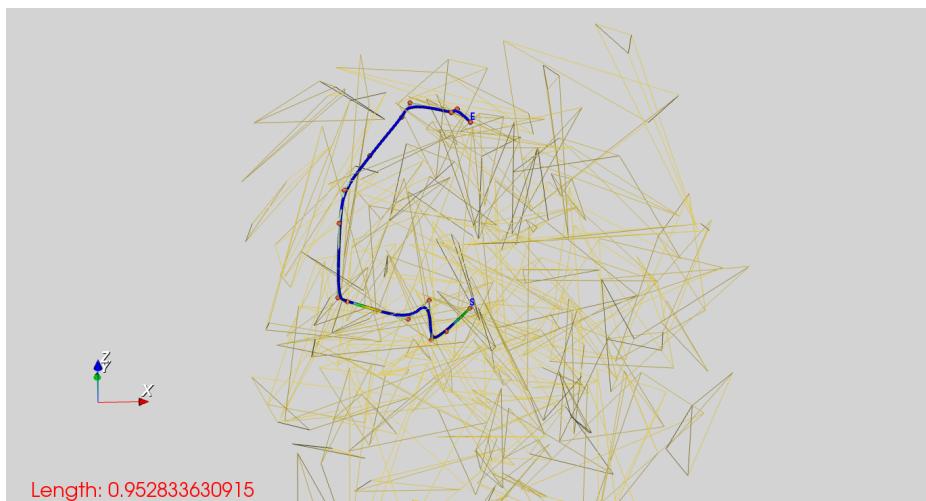
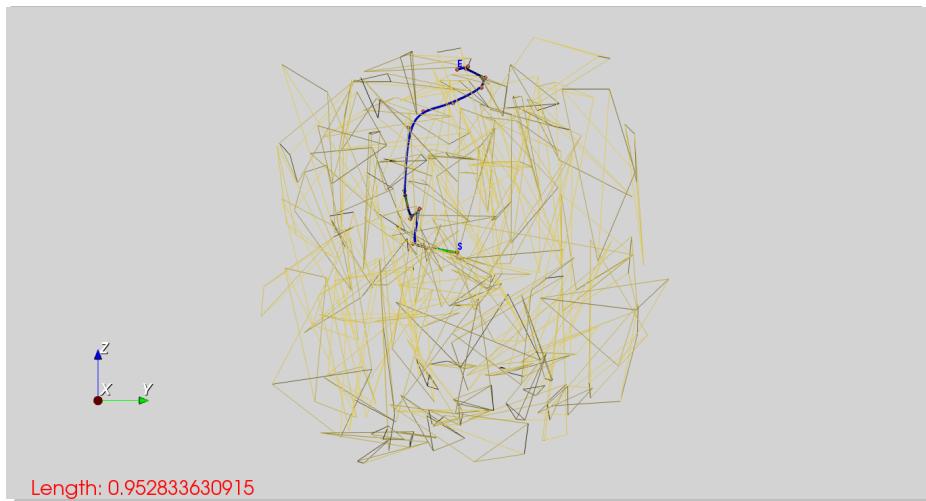


Figure 67.: Test 39; Scene 2;  $s \rightarrow e$   $[0.5, 0.5, 0.5] \rightarrow [0.5, 0.5, 0.95]$ ; Deg. 2; Meth. B; Post proc. X; Part. A.

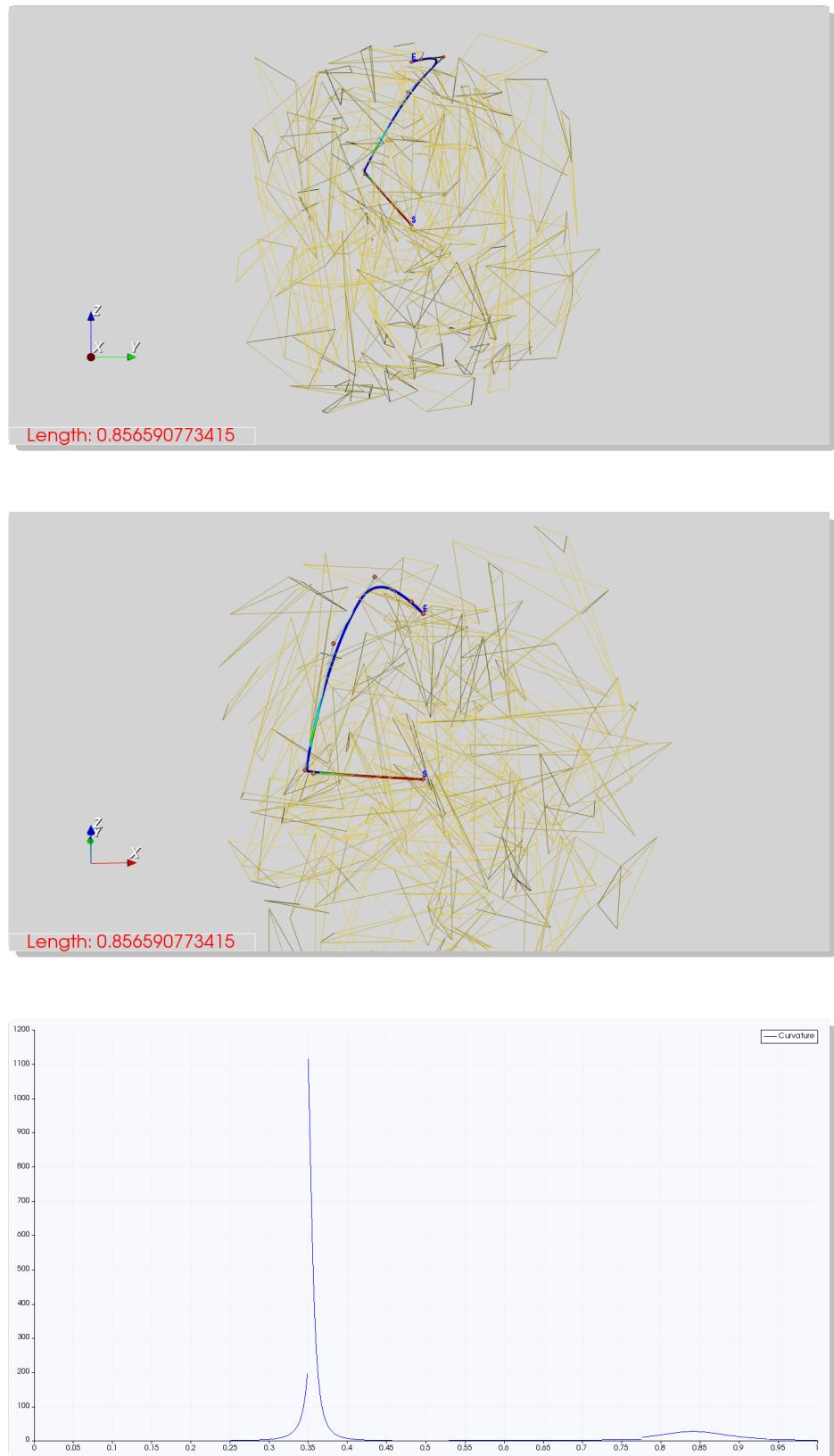


Figure 68.: Test 4o; Scene 2;  $s \rightarrow e$   $[0.5, 0.5, 0.5] \rightarrow [0.5, 0.5, 0.95]$ ; Deg. 2; Meth. B; Post proc. ✓; Part. A.

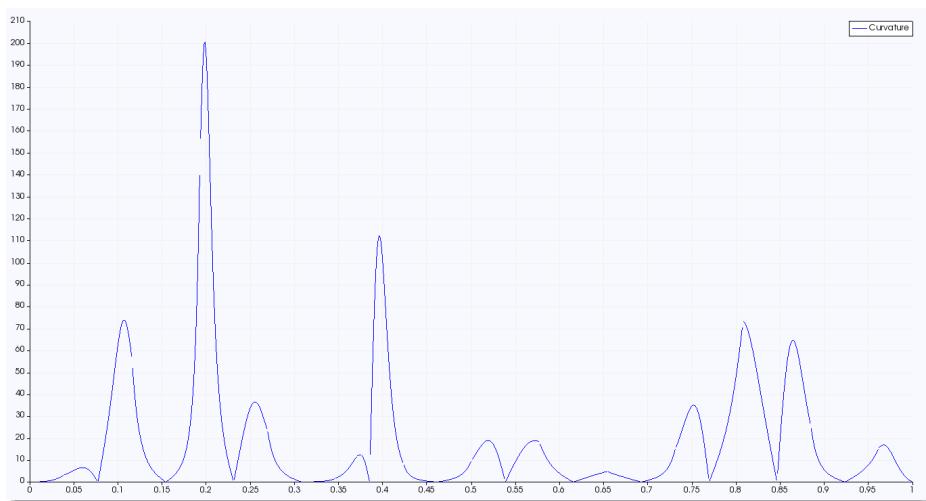


Figure 69.: Test 41; Scene 2;  $s \rightarrow e$   $[0.5,0.5,0.5] \rightarrow [0.5,0.5,0.95]$ ; Deg. 3; Meth. B; Post proc. X; Part. U.

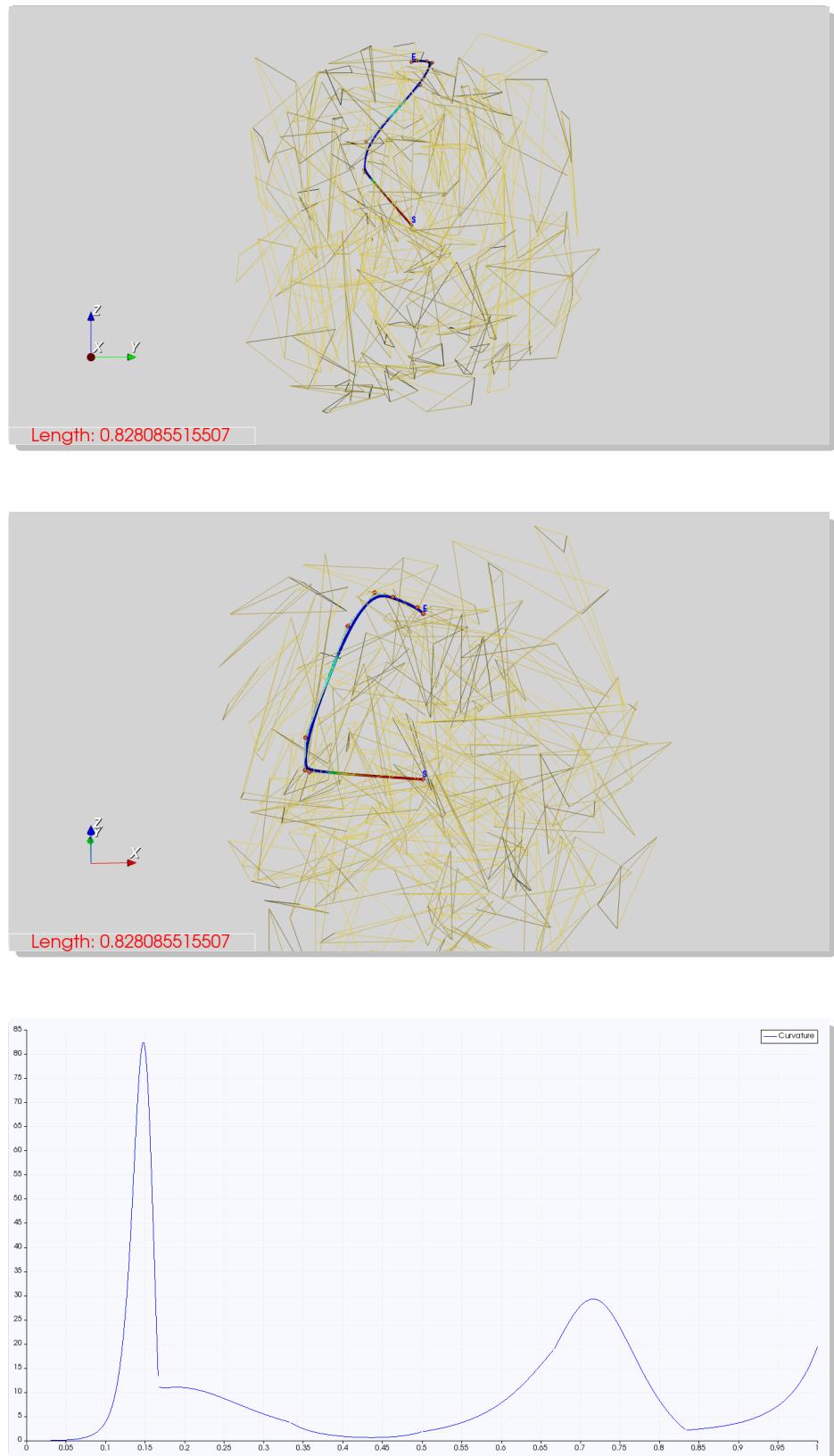


Figure 70.: Test 42; Scene 2;  $s \rightarrow e$   $[0.5, 0.5, 0.5] \rightarrow [0.5, 0.5, 0.95]$ ; Deg. 3; Meth. B; Post proc. ✓; Part. U.

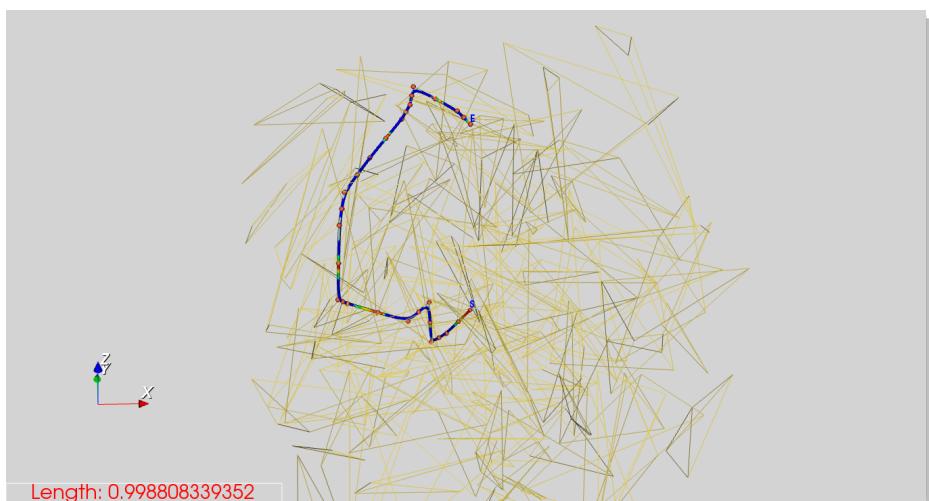
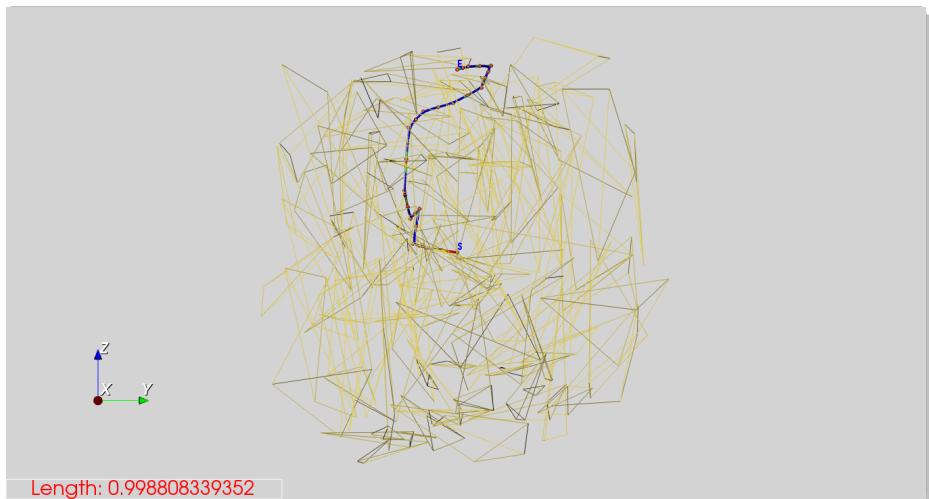


Figure 71.: Test 43; Scene 2;  $s \rightarrow e$   $[0.5,0.5,0.5] \rightarrow [0.5,0.5,0.95]$ ; Deg. 3; Meth. B; Post proc. X; Part. A.

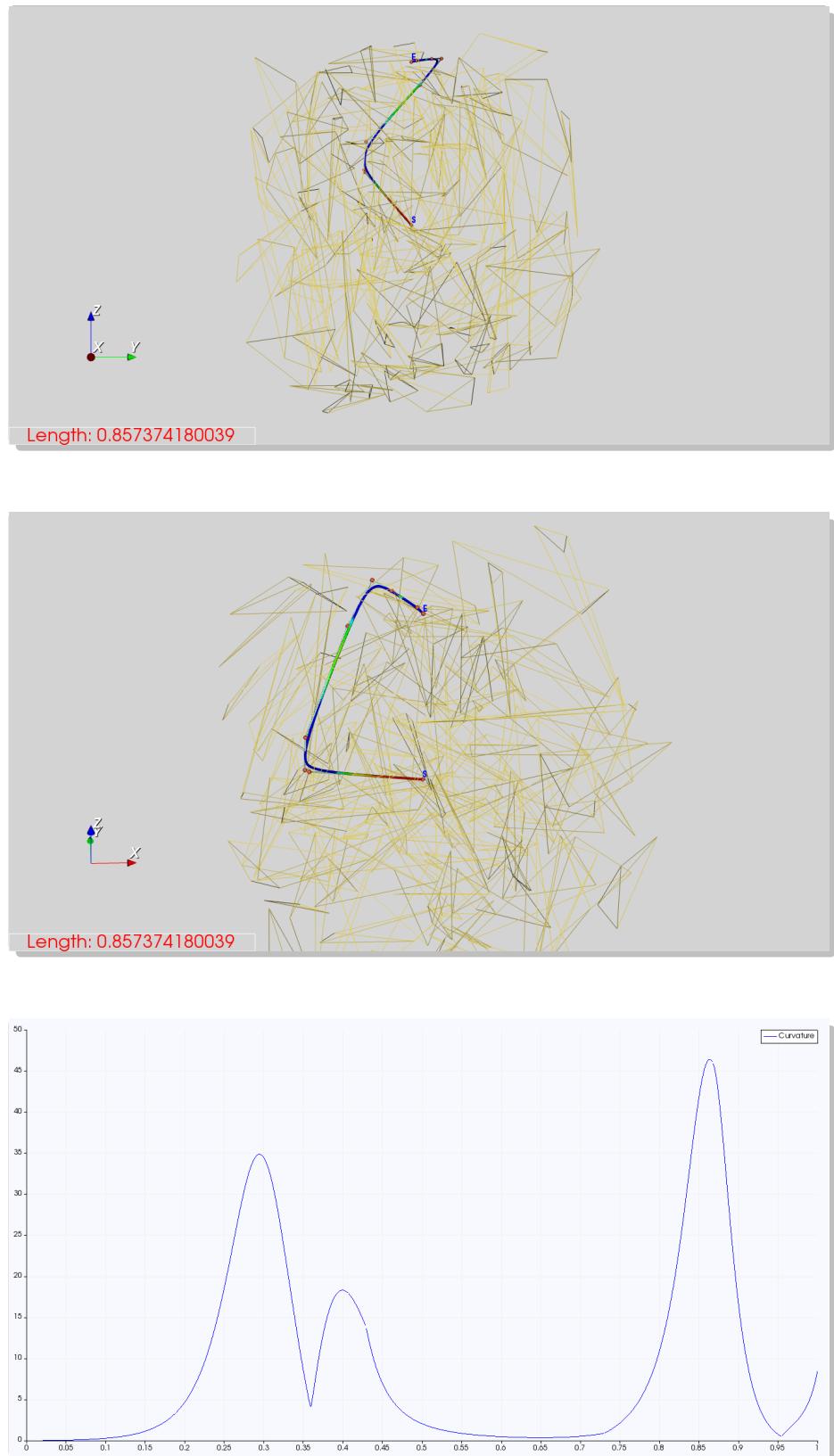


Figure 72.: Test 44; Scene 2;  $s \rightarrow e$   $[0.5,0.5,0.5] \rightarrow [0.5,0.5,0.95]$ ; Deg. 3; Meth. B; Post proc. ✓; Part. A.

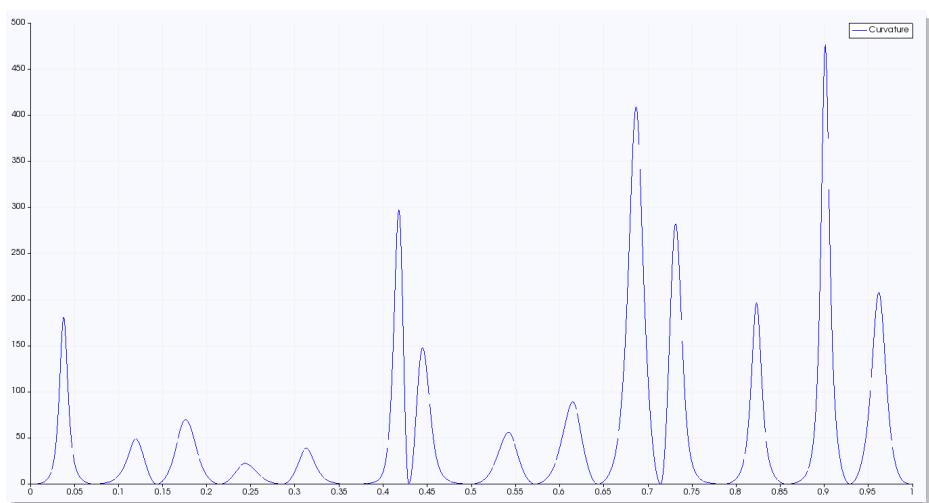
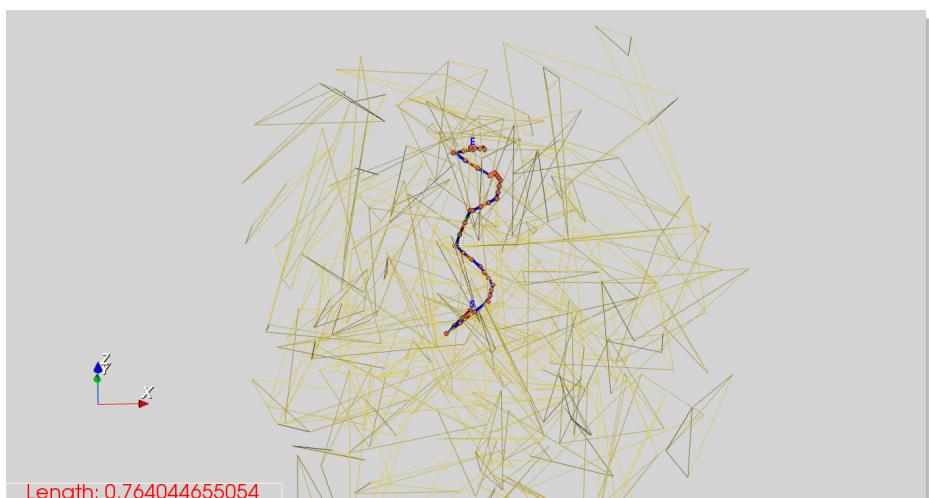
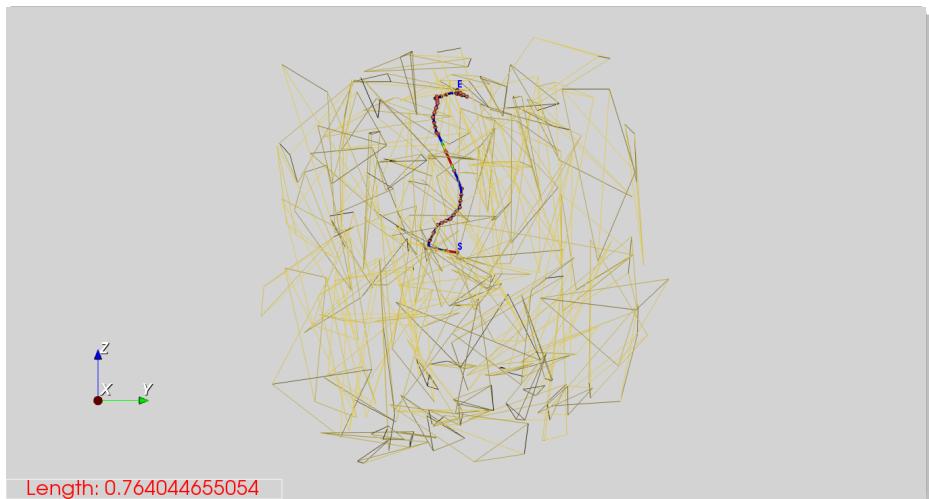


Figure 73.: Test 45; Scene 2;  $s \rightarrow e$   $[0.5, 0.5, 0.5] \rightarrow [0.5, 0.5, 0.95]$ ; Deg. 4; Meth. B; Post proc. X; Part. U.

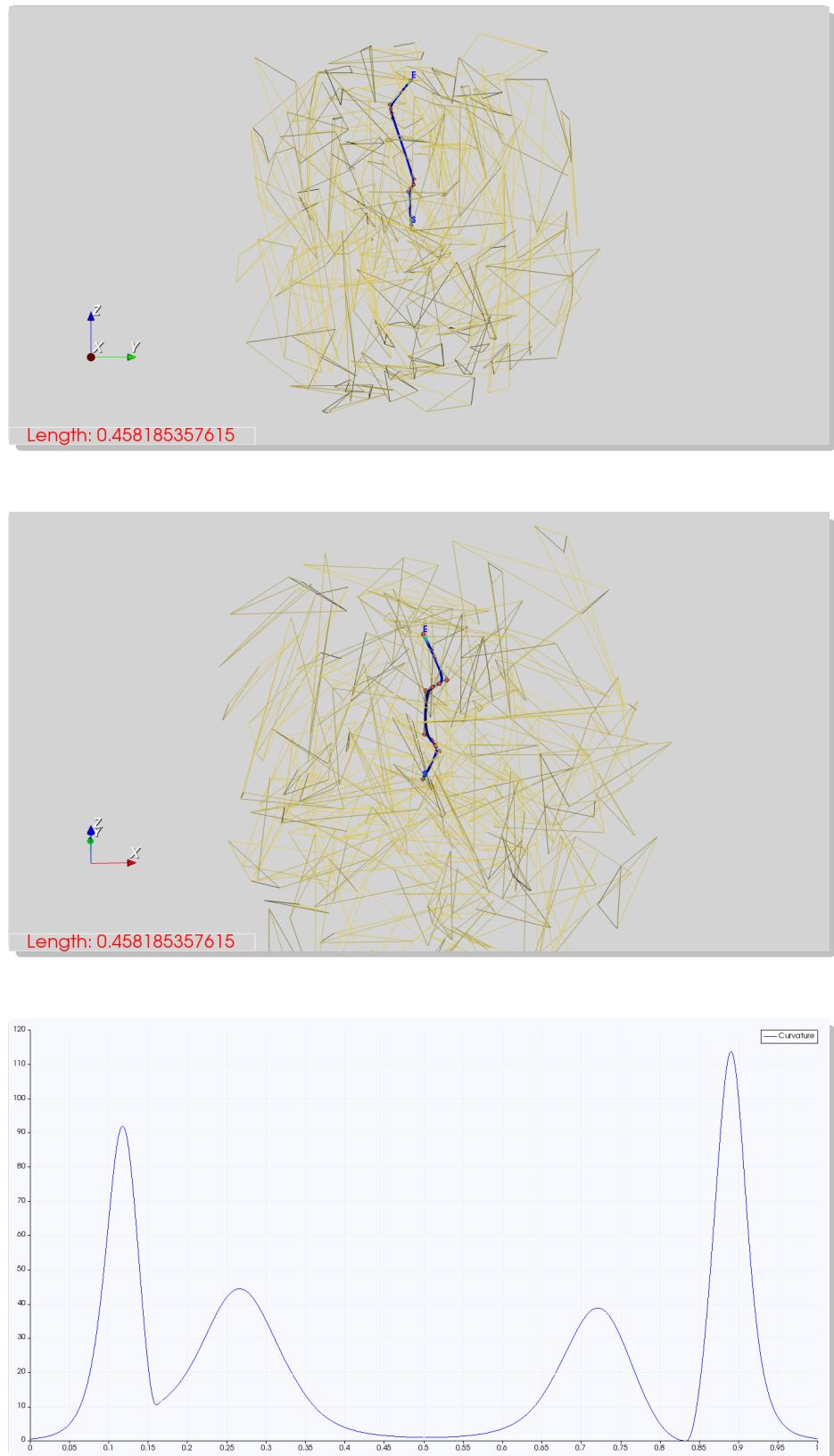


Figure 74.: Test 46; Scene 2;  $s \rightarrow e$   $[0.5, 0.5, 0.5] \rightarrow [0.5, 0.5, 0.95]$ ; Deg. 4; Meth. B; Post proc. ✓; Part. U.

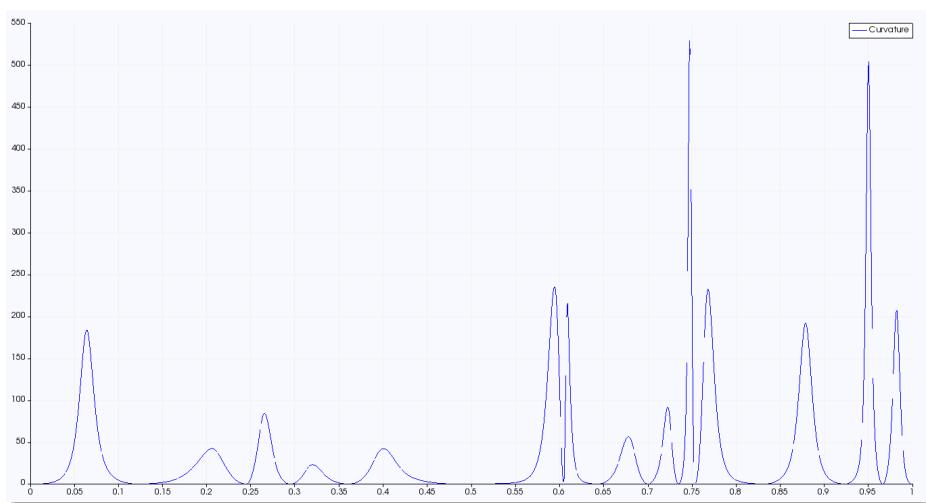
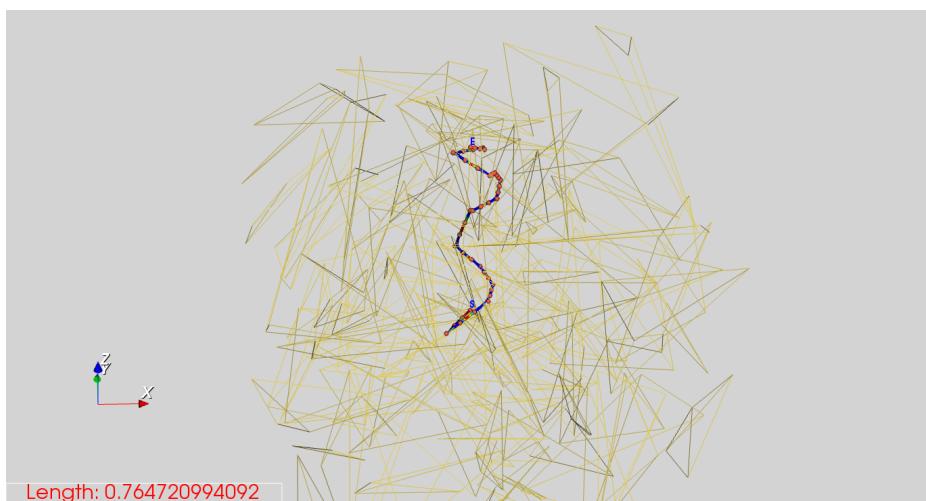
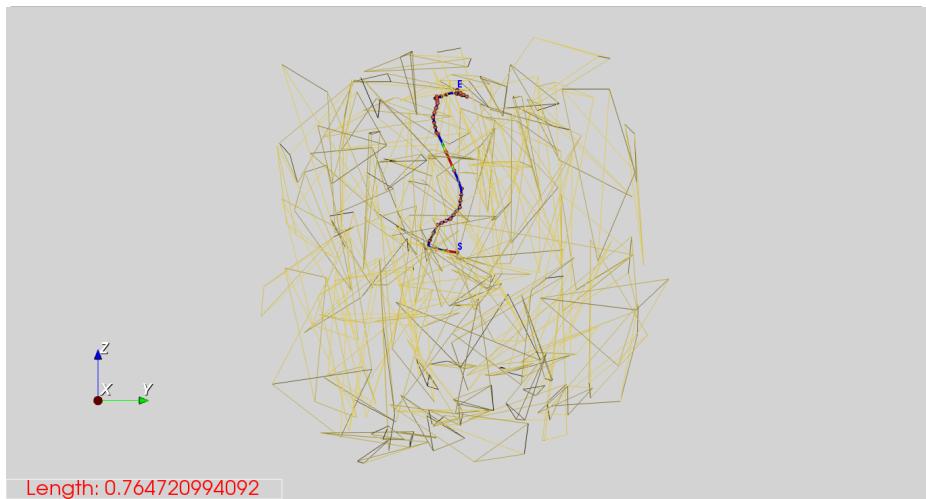


Figure 75.: Test 47; Scene 2;  $s \rightarrow e$   $[0.5, 0.5, 0.5] \rightarrow [0.5, 0.5, 0.95]$ ; Deg. 4; Meth. B; Post proc. X; Part. A.

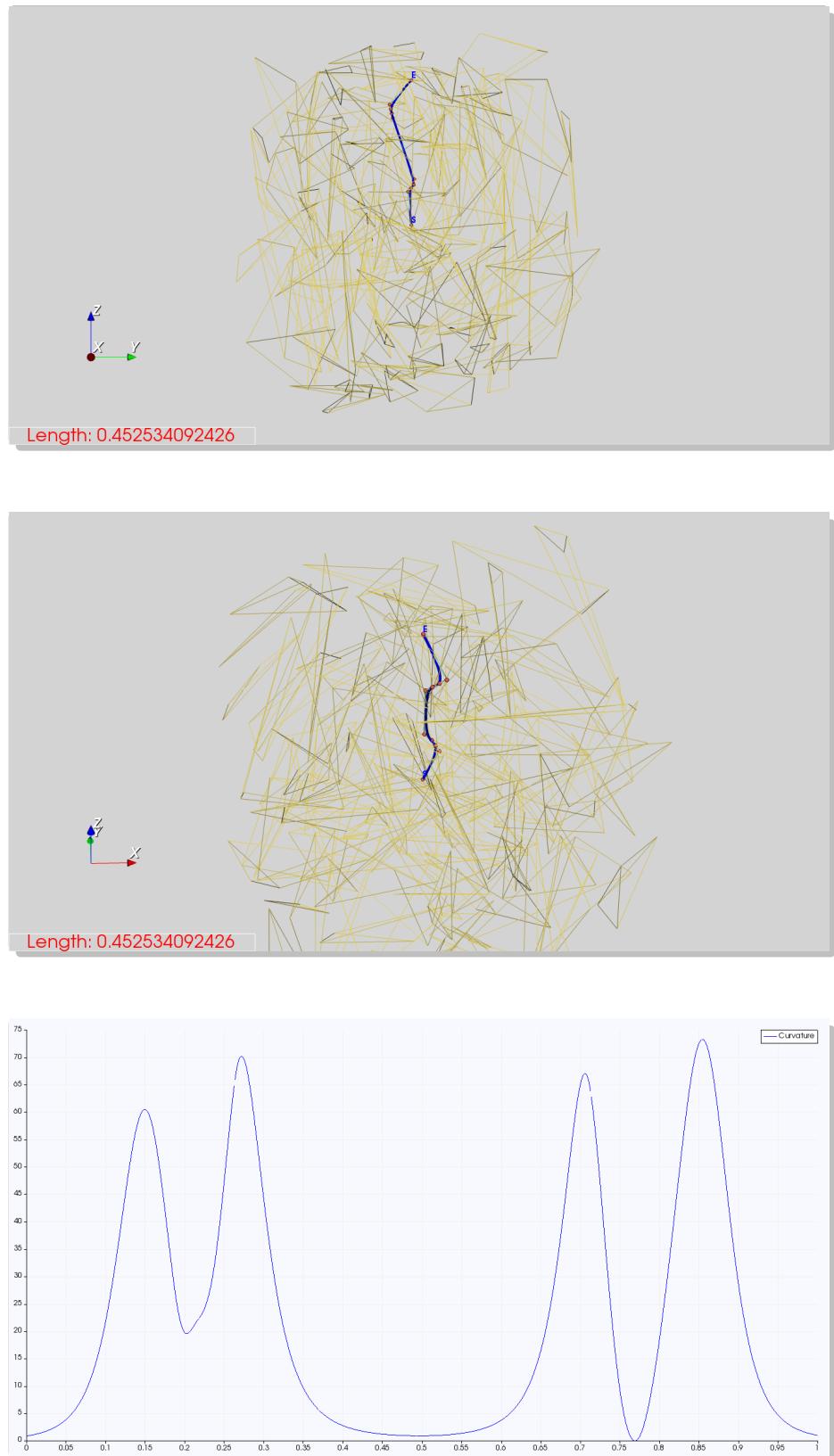


Figure 76.: Test 48; Scene 2;  $s \rightarrow e$   $[0.5, 0.5, 0.5] \rightarrow [0.5, 0.5, 0.95]$ ; Deg. 4; Meth. B; Post proc. ✓; Part. A.

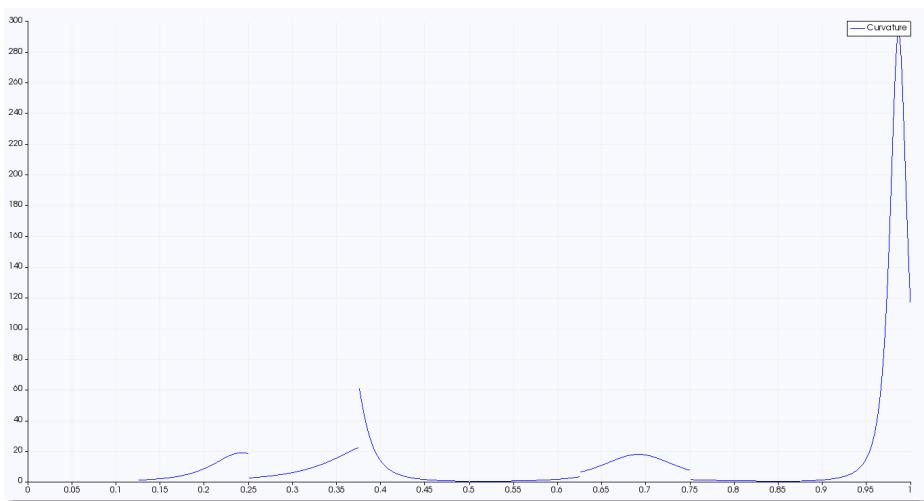
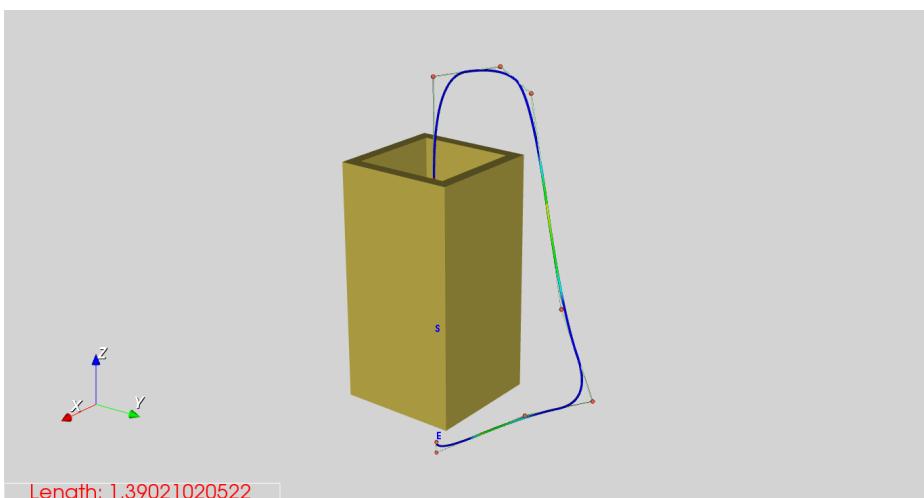
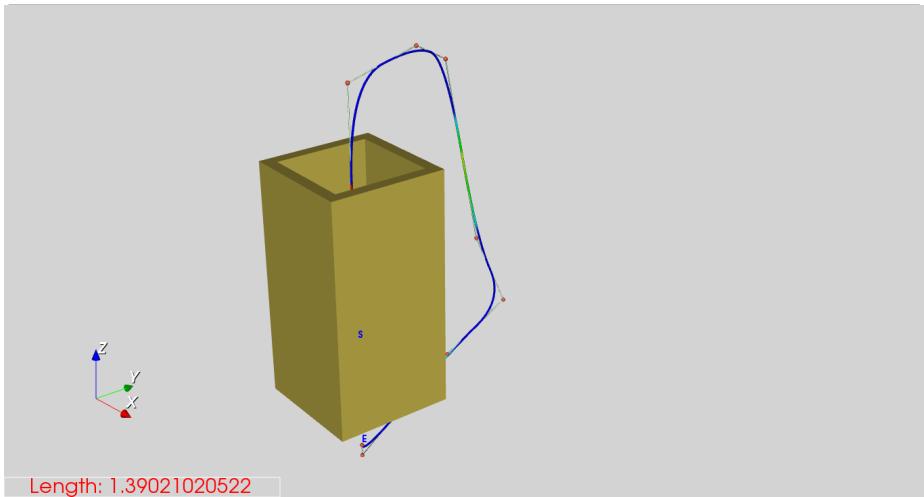


Figure 77.: Test 49; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 2; Meth. A; Post proc. X; Part. U.

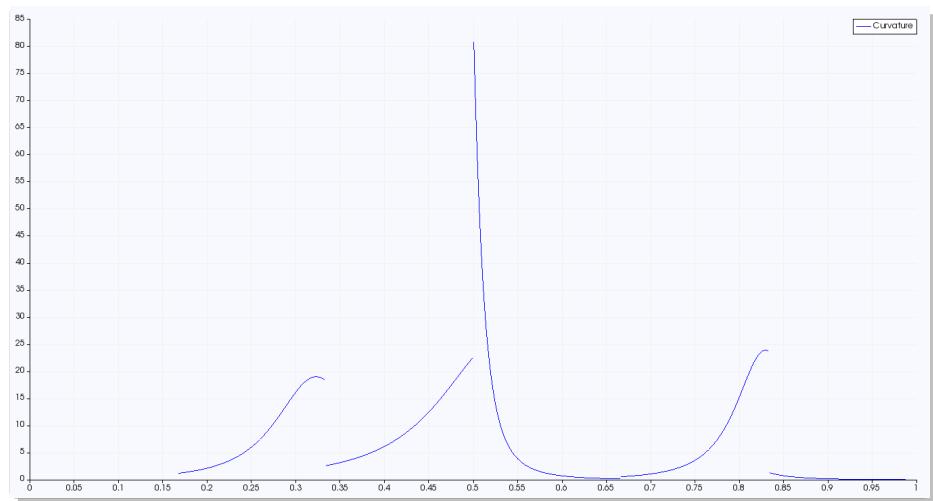
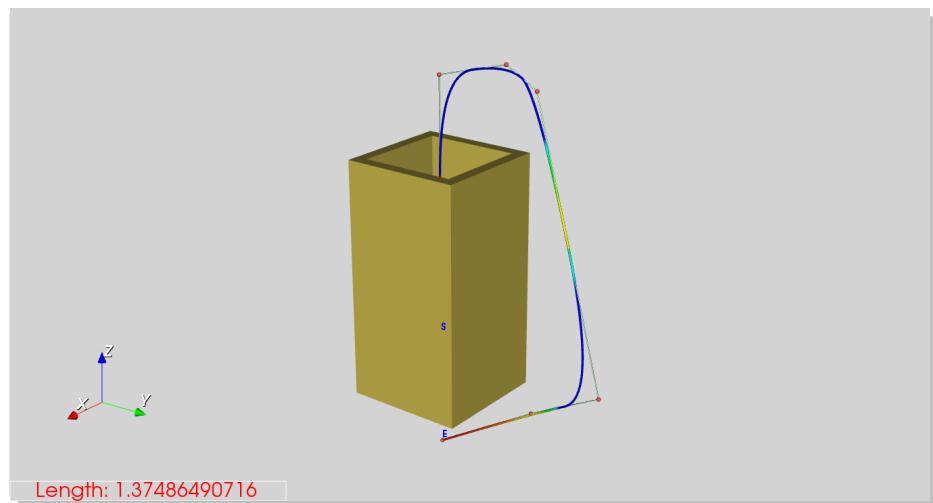
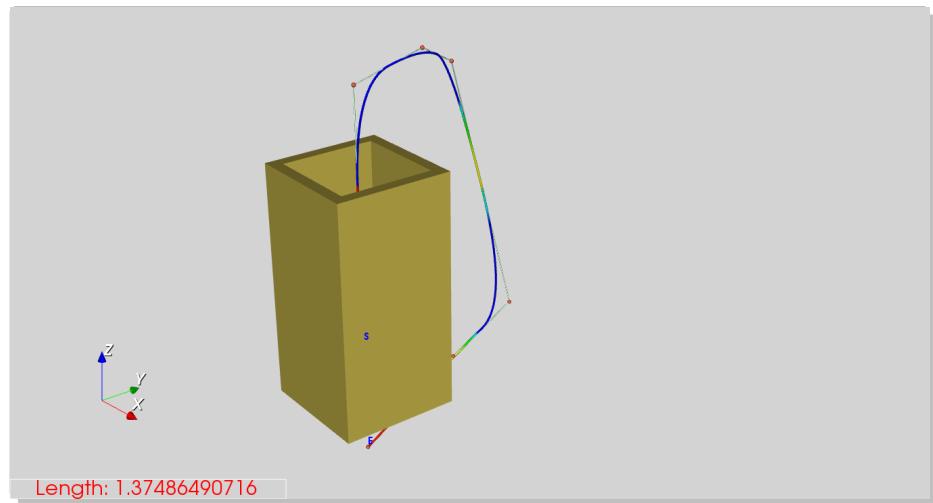


Figure 78.: Test 50; Scene 3;  $s \rightarrow e [0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 2; Meth. A; Post proc. ✓; Part. U.

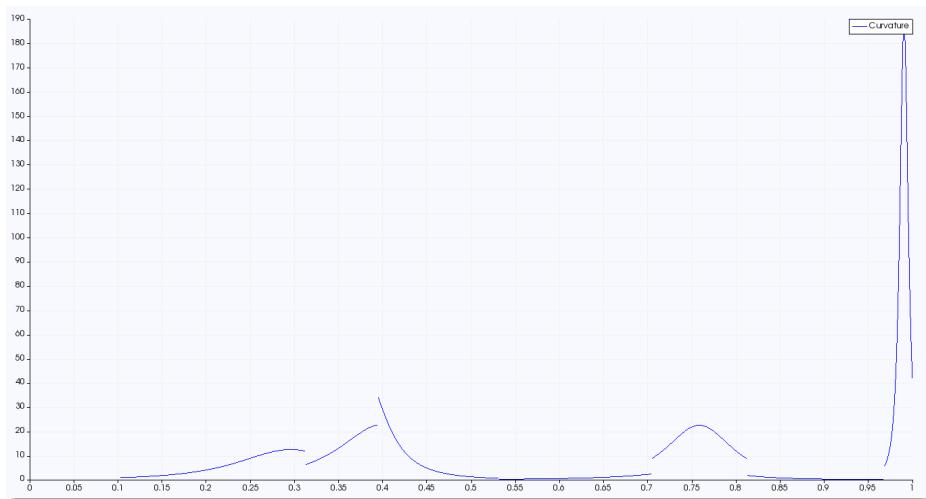
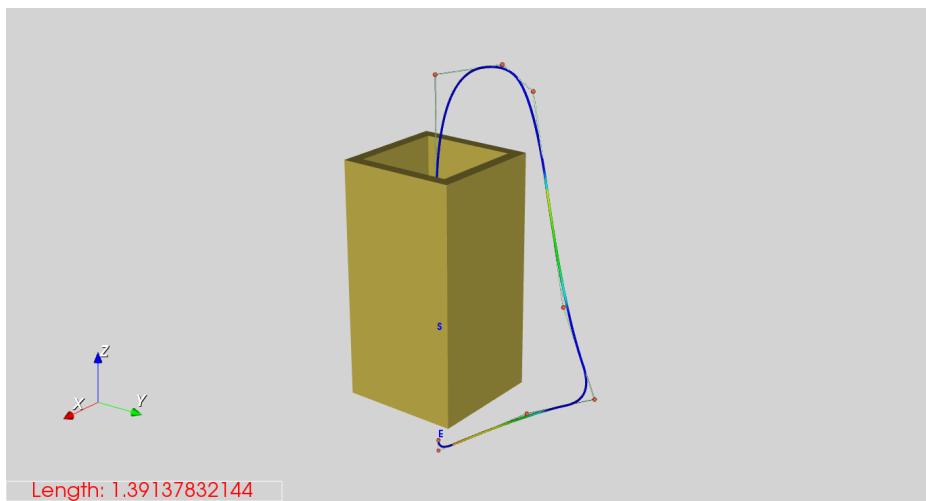
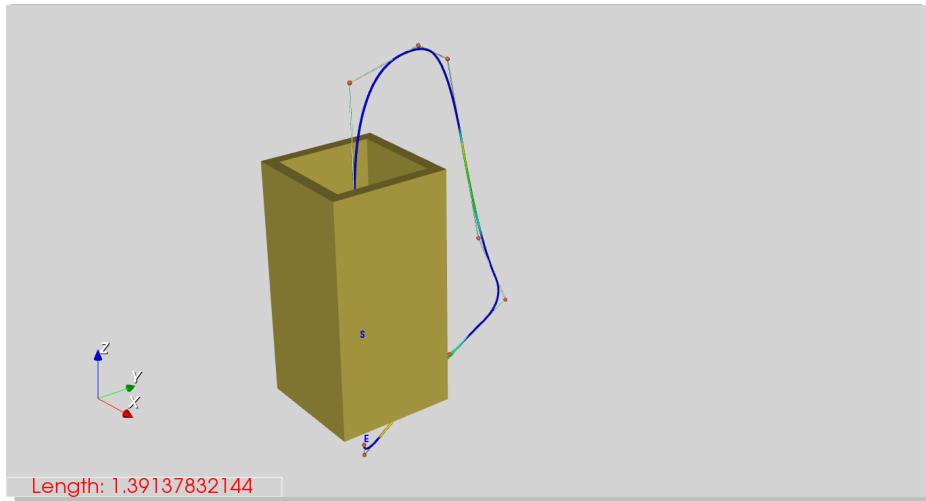


Figure 79.: Test 51; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 2; Meth. A; Post proc. X; Part. A.

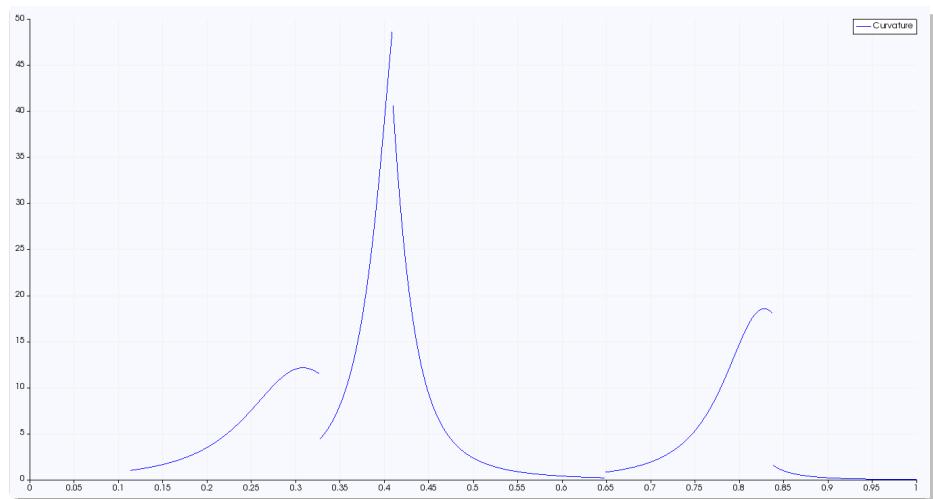
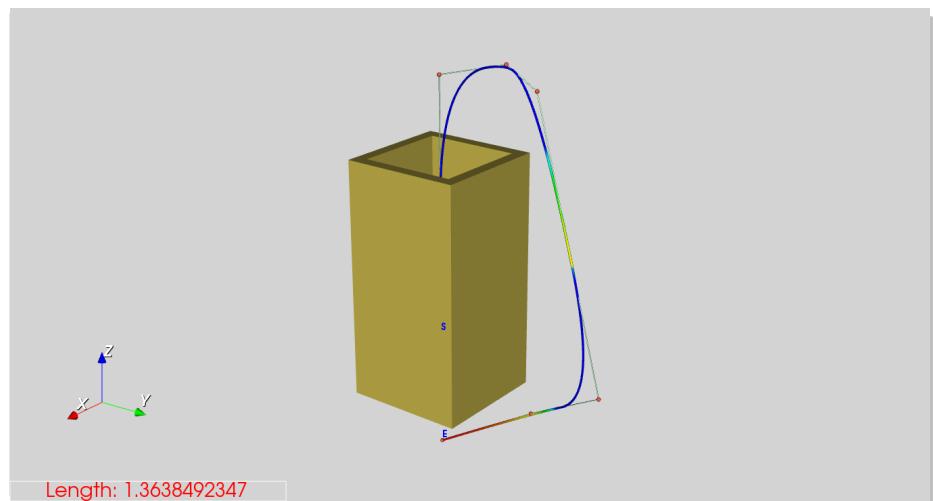
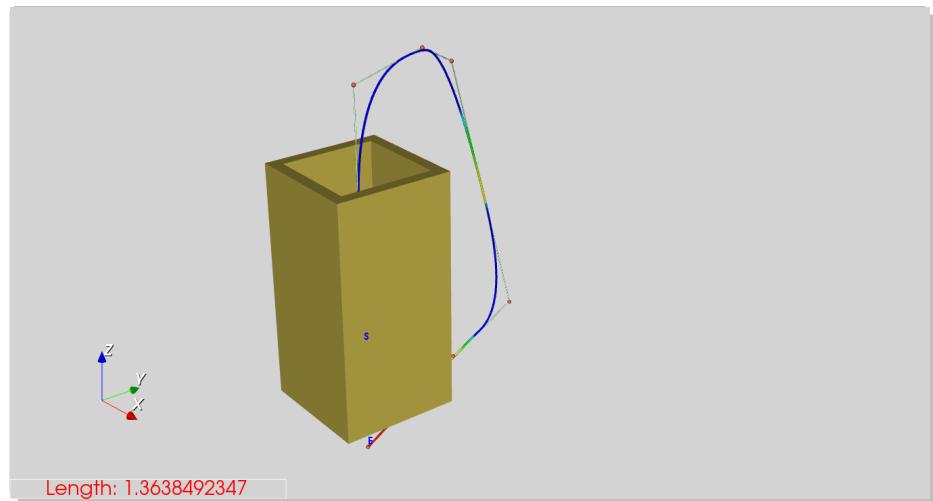


Figure 8o.: Test 52; Scene 3;  $s \rightarrow e [0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 2; Meth. A; Post proc. ✓; Part. A.

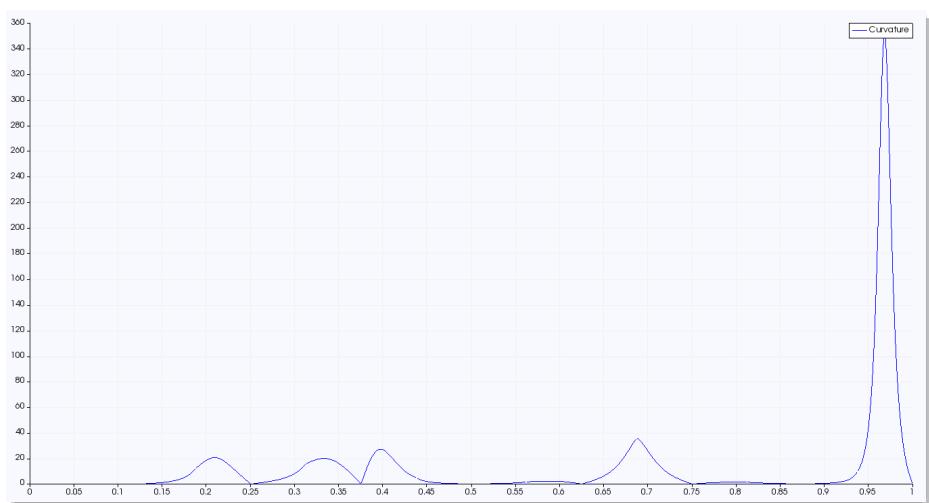
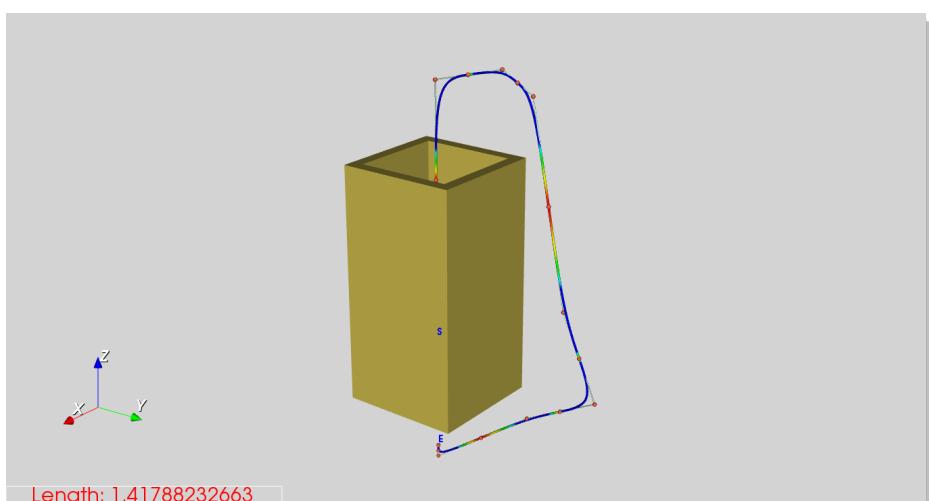
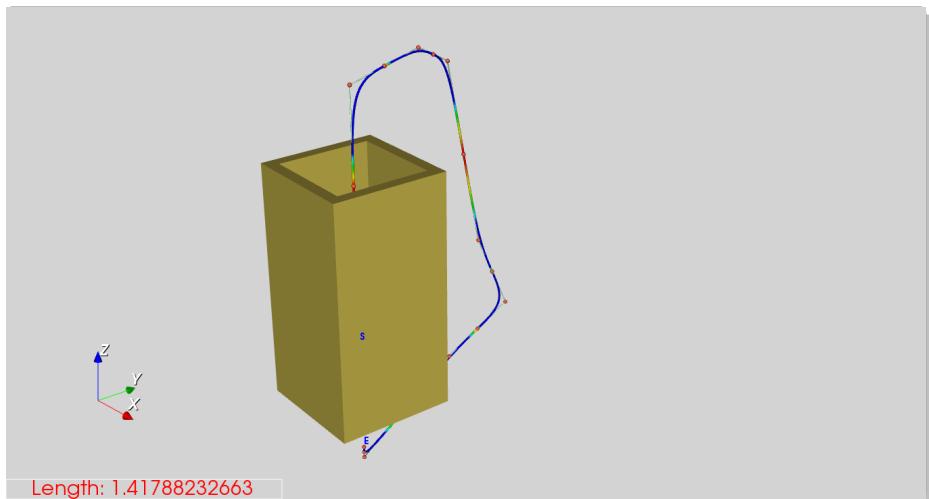


Figure 81.: Test 53; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 3; Meth. A; Post proc. X; Part. U.

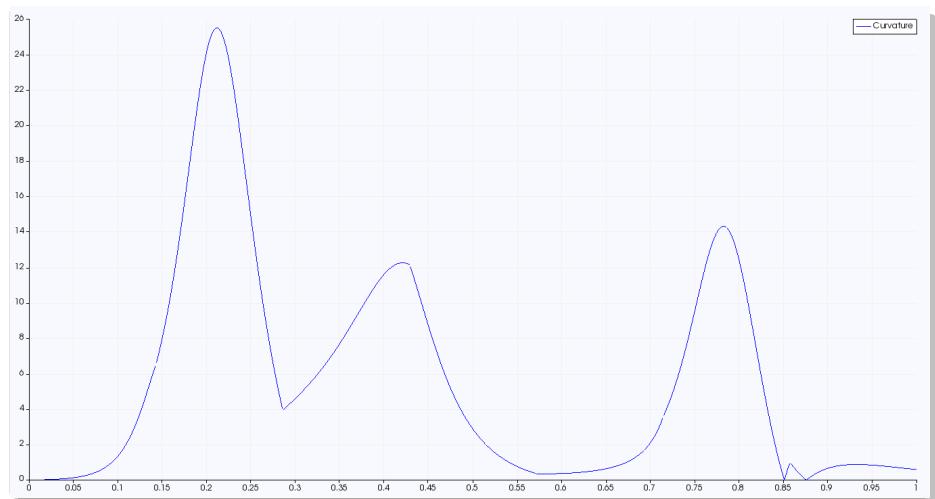
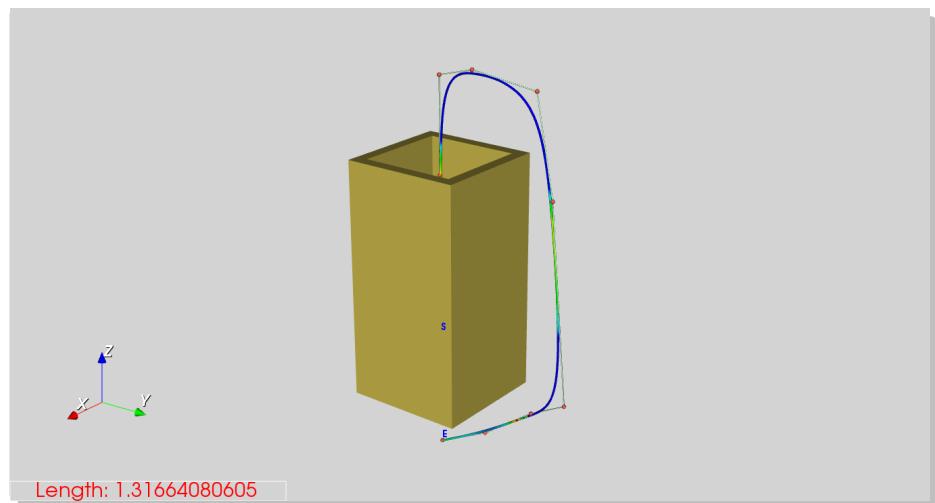
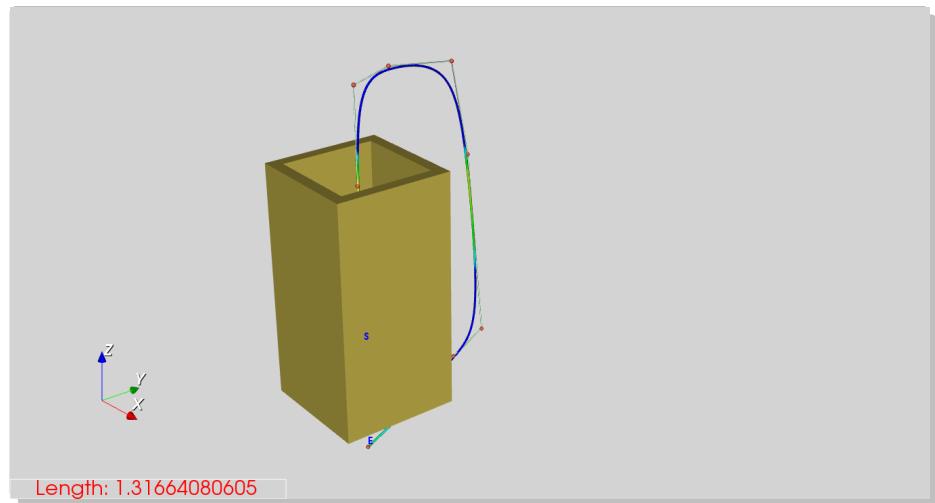


Figure 82.: Test 54; Scene 3;  $s \rightarrow e [0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 3; Meth. A; Post proc. ✓; Part. U.

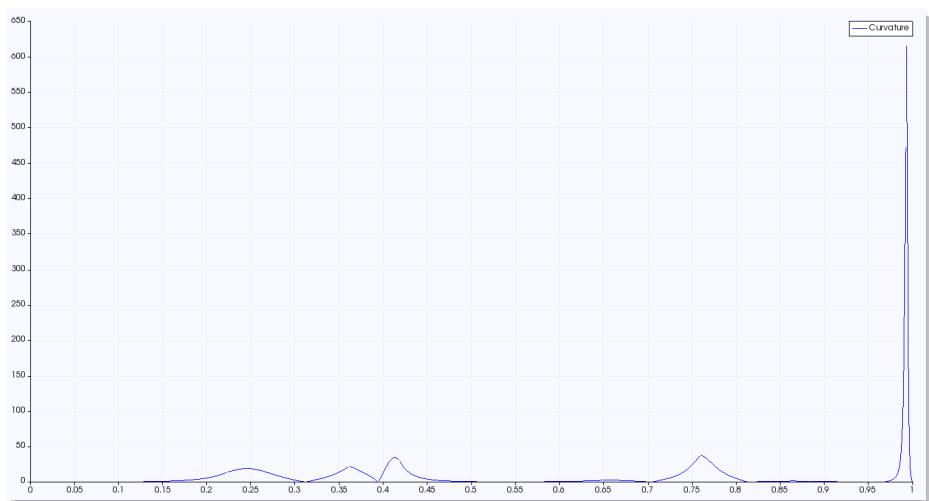
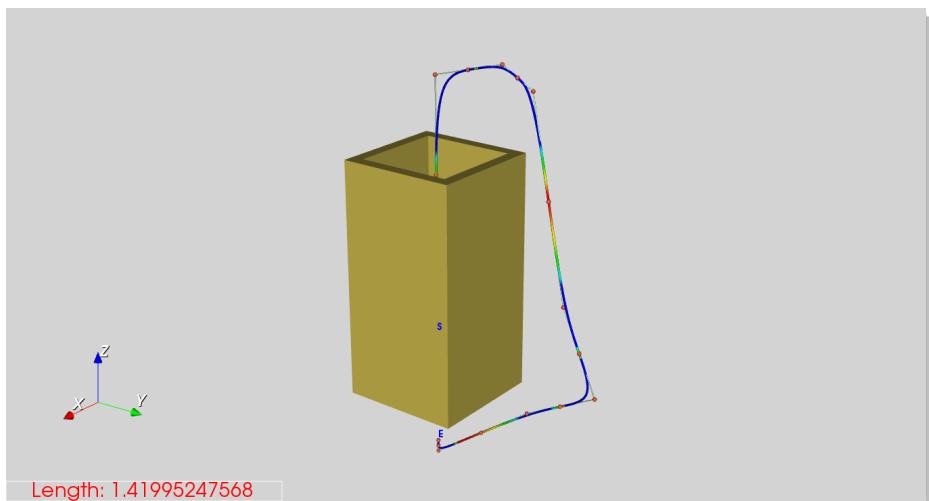
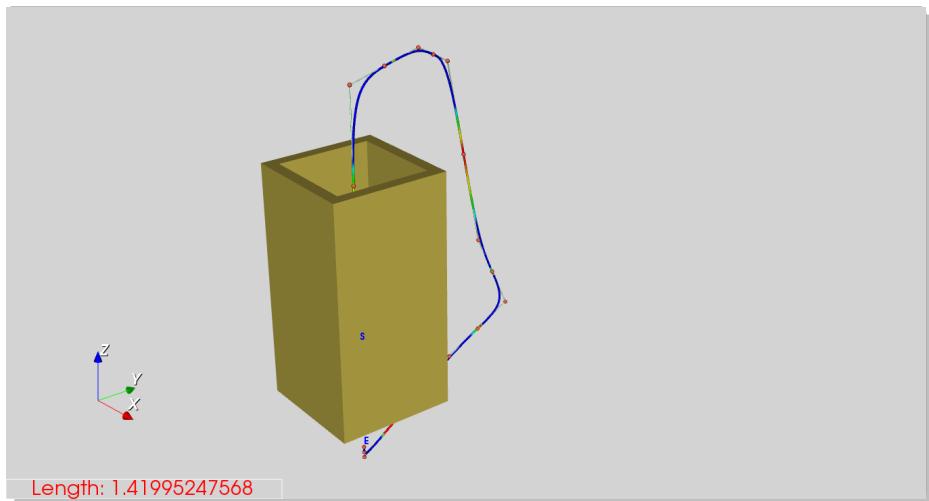


Figure 83.: Test 55; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 3; Meth. A; Post proc. X; Part. A.

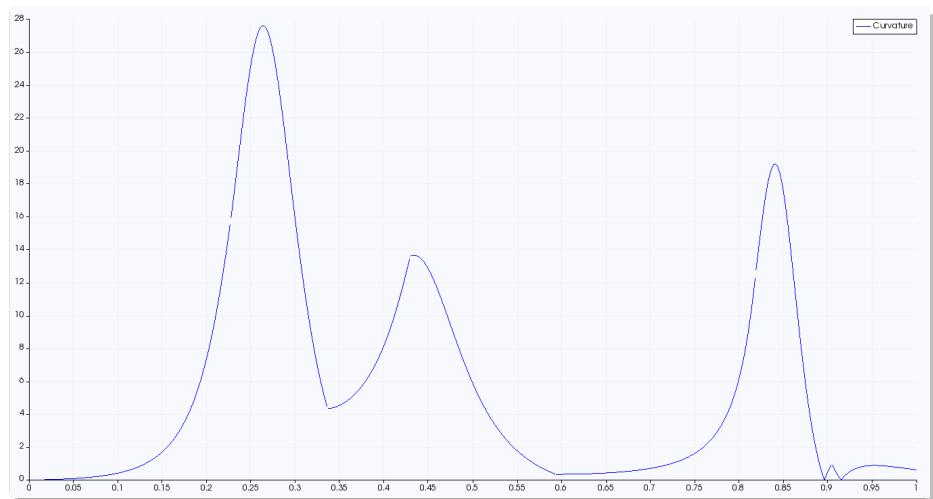
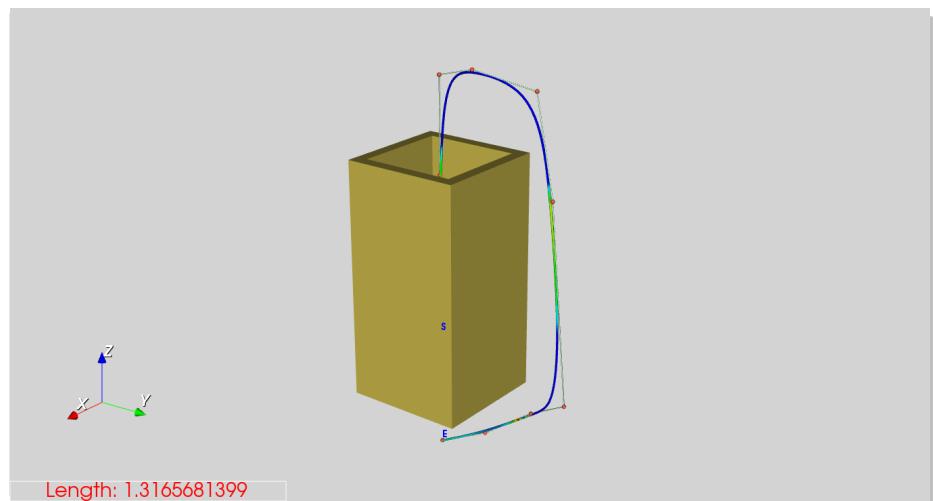
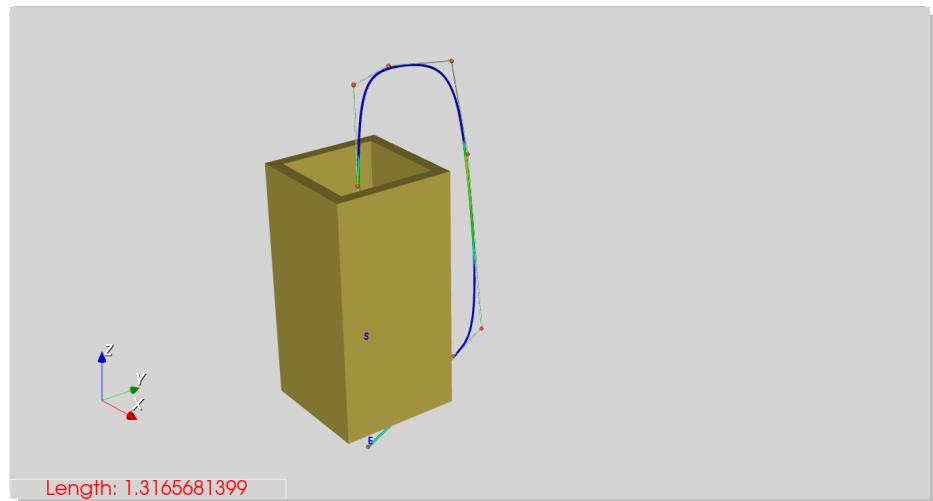


Figure 84.: Test 56; Scene 3;  $s \rightarrow e [0.5,0.5,0.4] \rightarrow [0.5,0.5,0.2]$ ; Deg. 3; Meth. A; Post proc. ✓; Part. A.

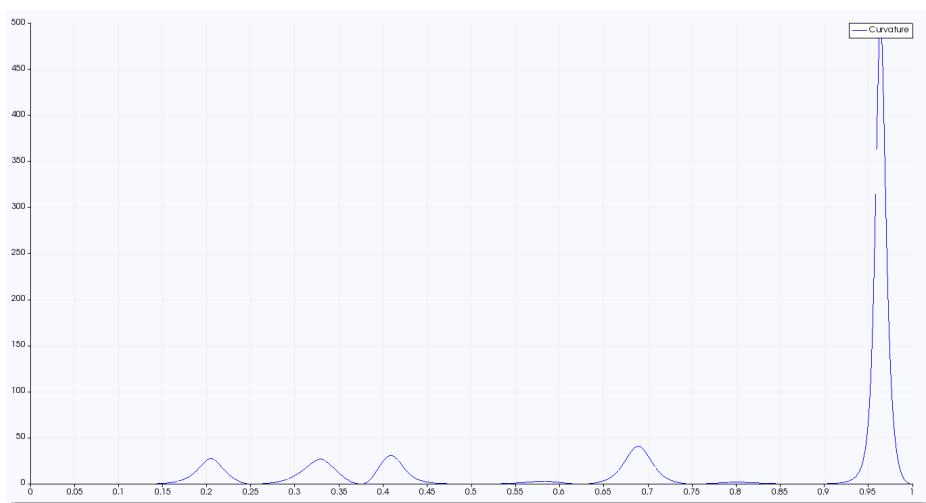
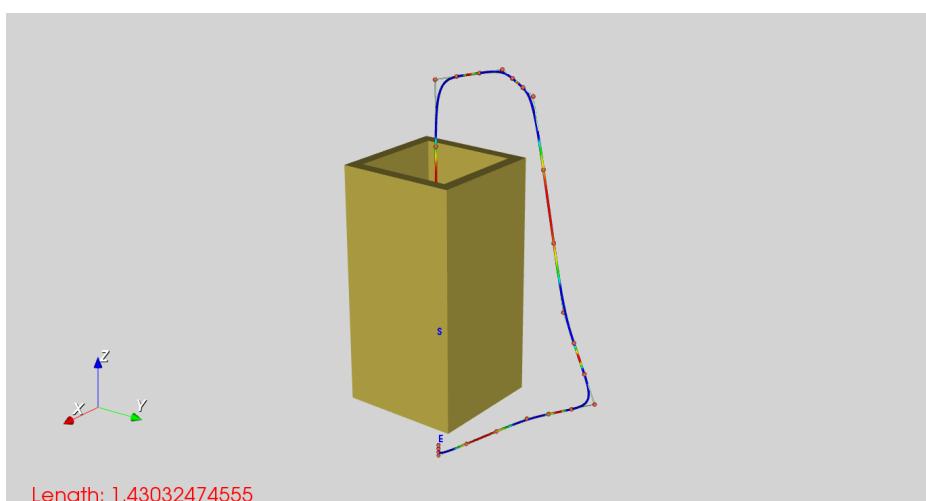
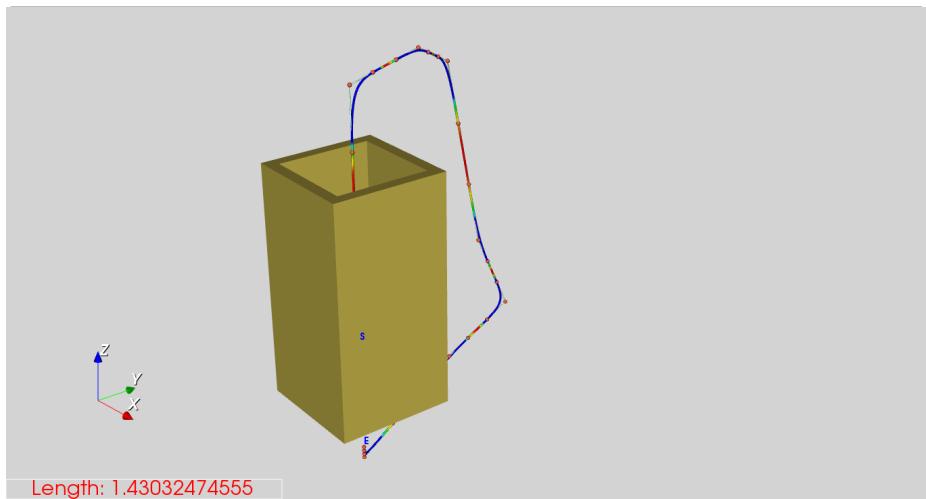


Figure 85.: Test 57; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 4; Meth. A; Post proc. X; Part. U.

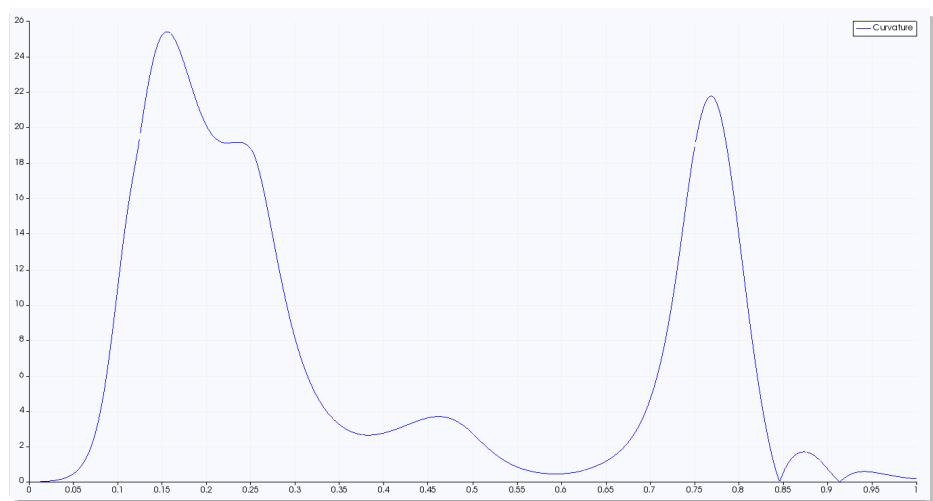
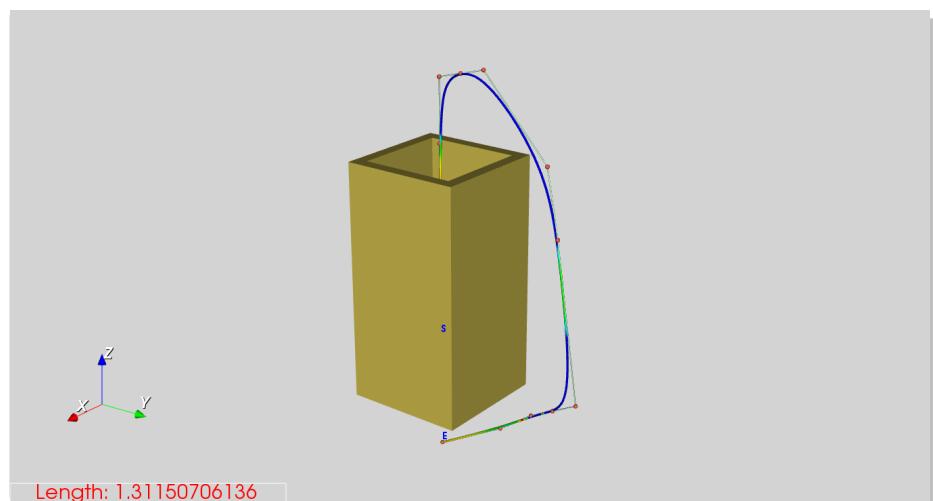
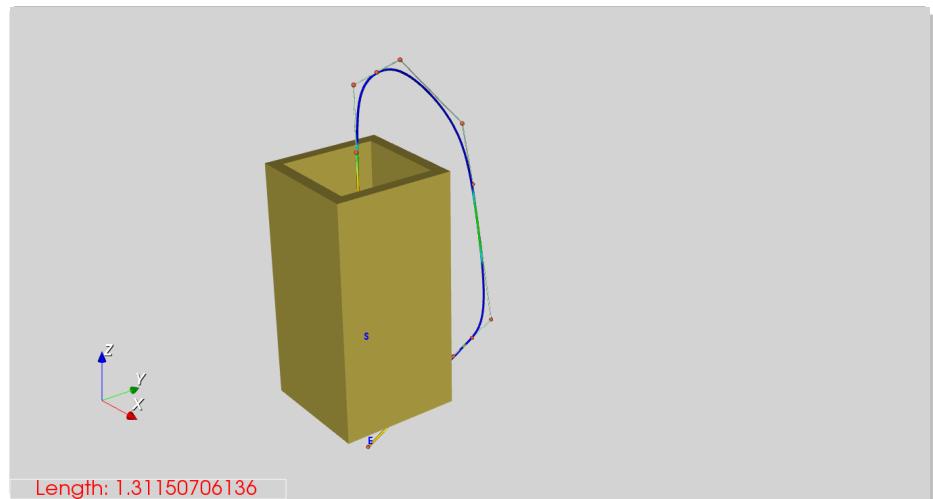


Figure 86.: Test 58; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 4; Meth. A; Post proc. ✓; Part. U.

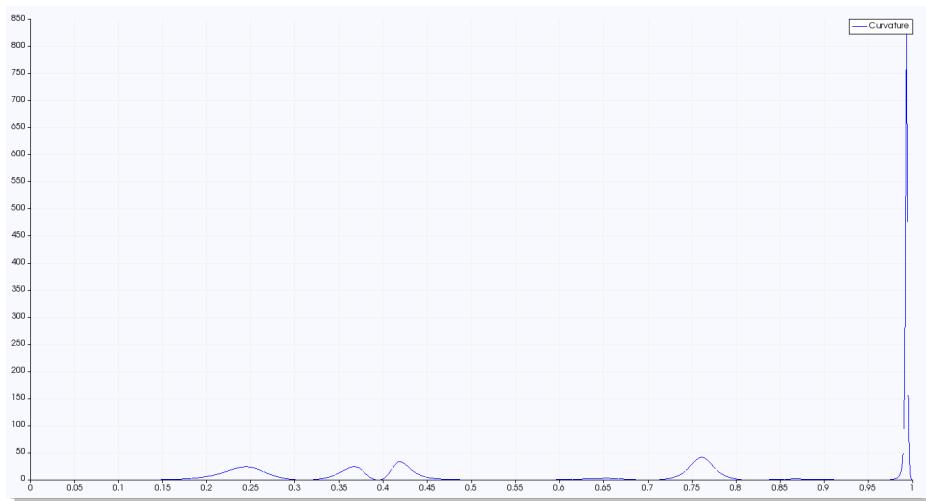
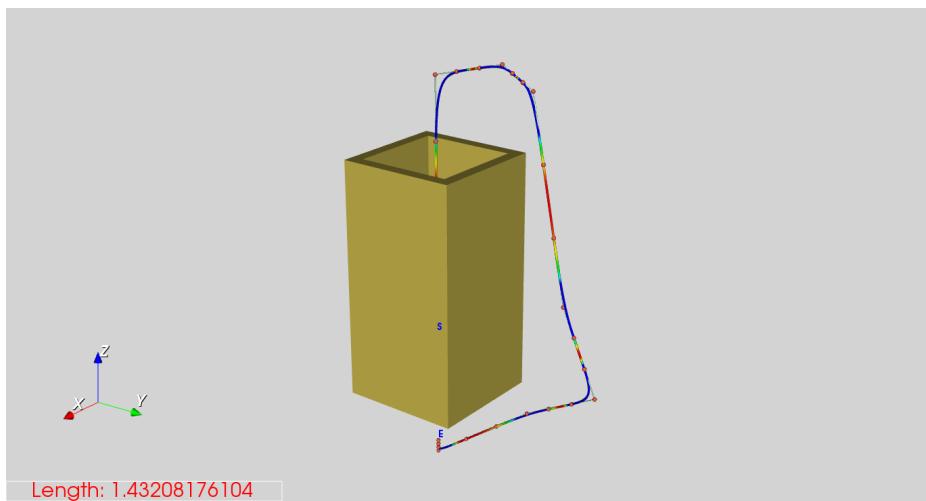
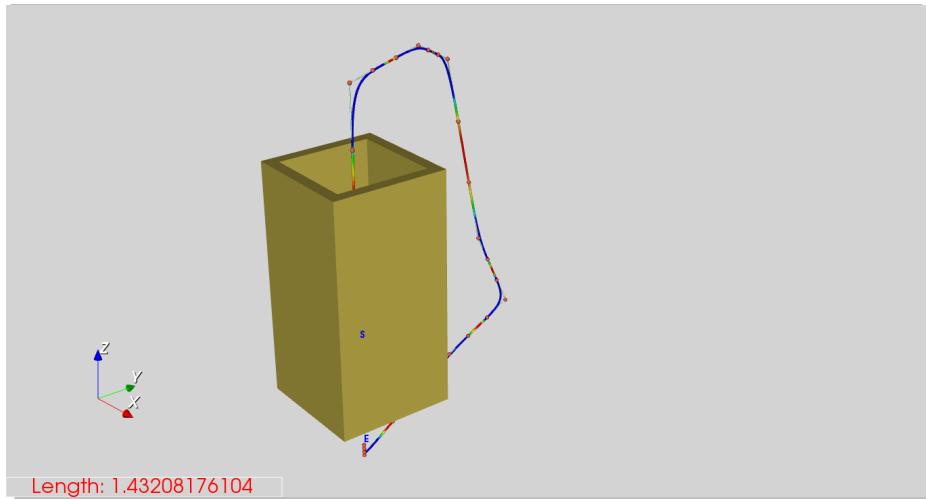


Figure 87.: Test 59; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 4; Meth. A; Post proc. X; Part. A.

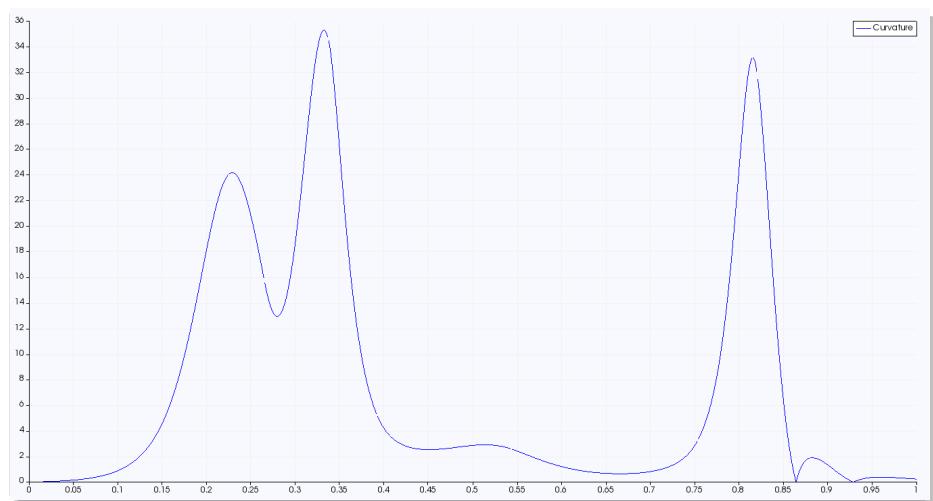
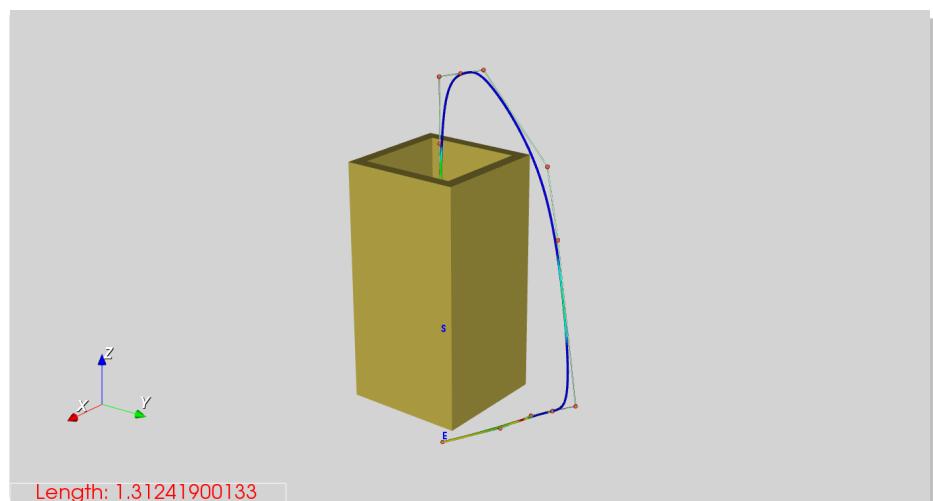
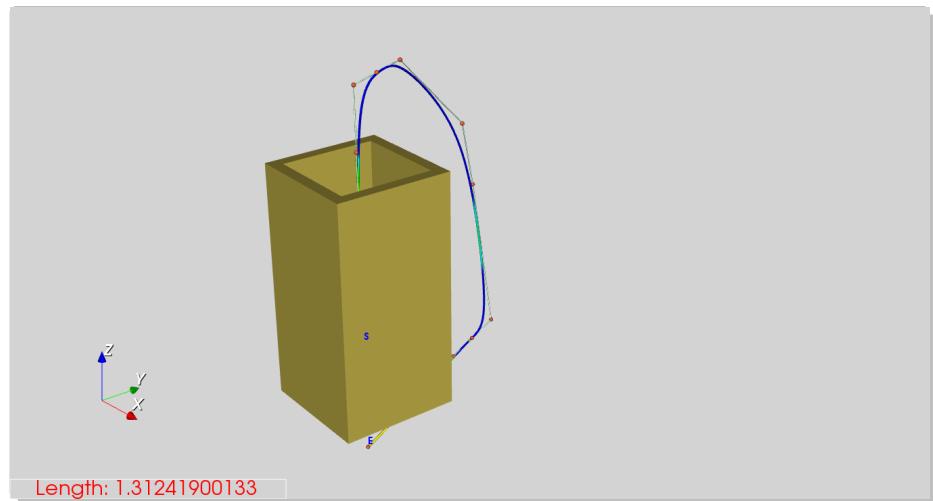


Figure 88.: Test 6o; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 4; Meth. A; Post proc. ✓; Part. A.

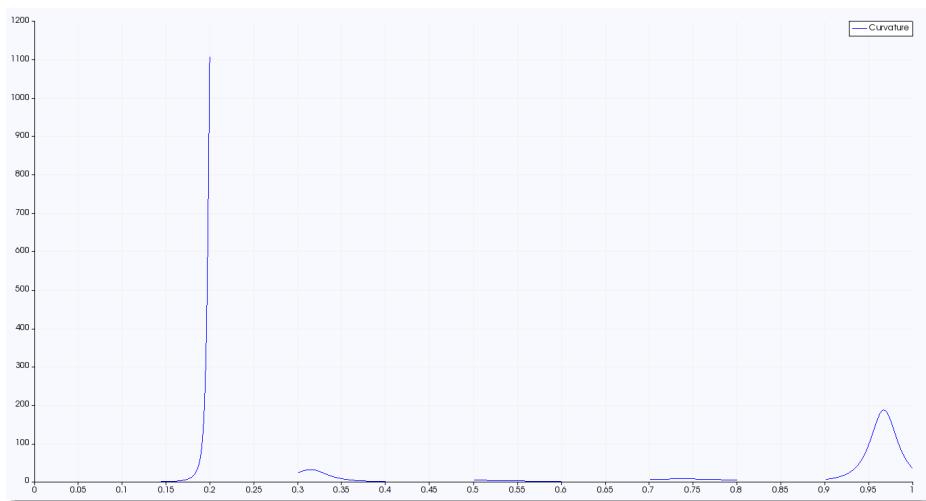
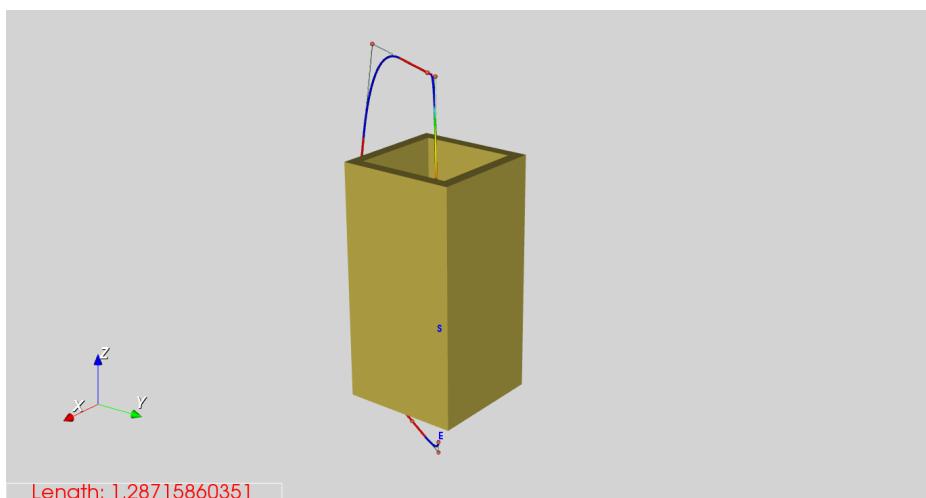
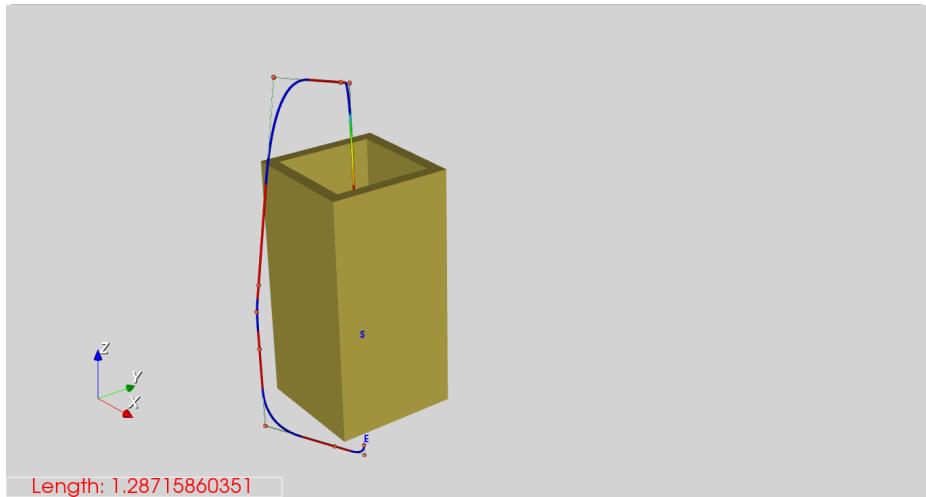


Figure 89.: Test 61; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 2; Meth. B; Post proc.  $\chi$ ; Part. U.

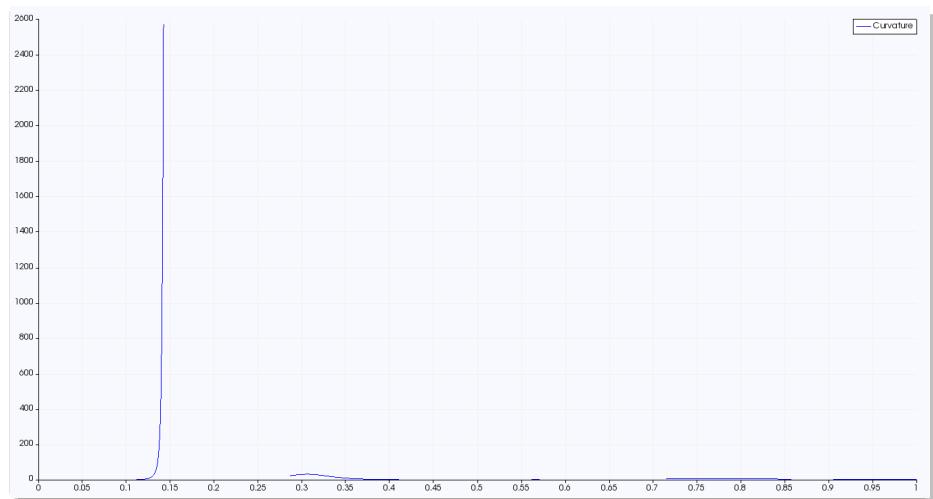
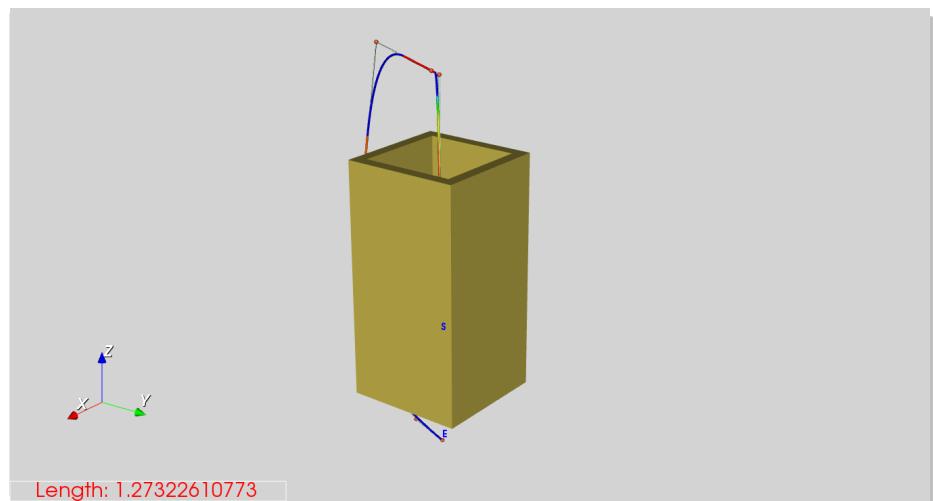
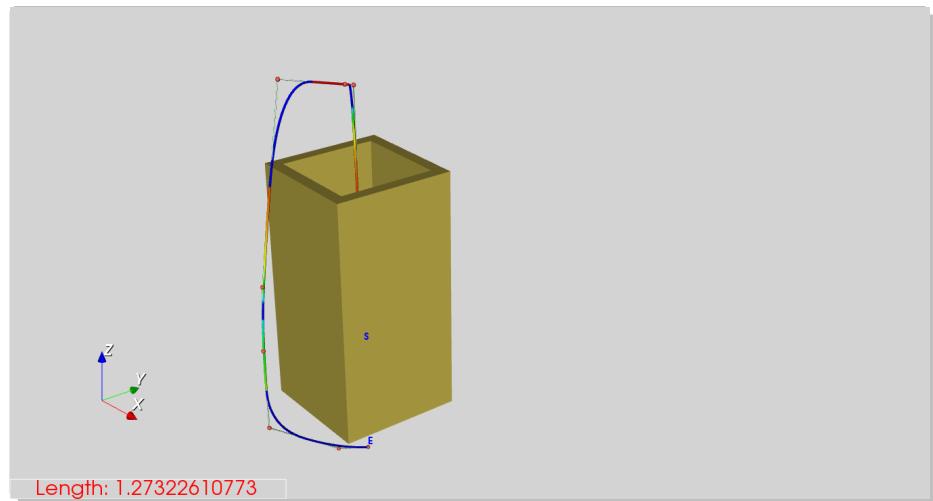


Figure 90.: Test 62; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 2; Meth. B; Post proc. ✓; Part. U.

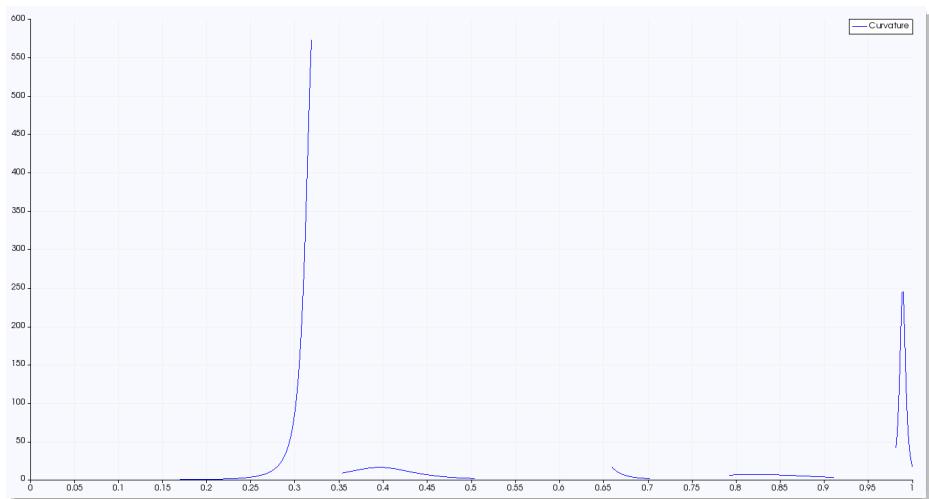
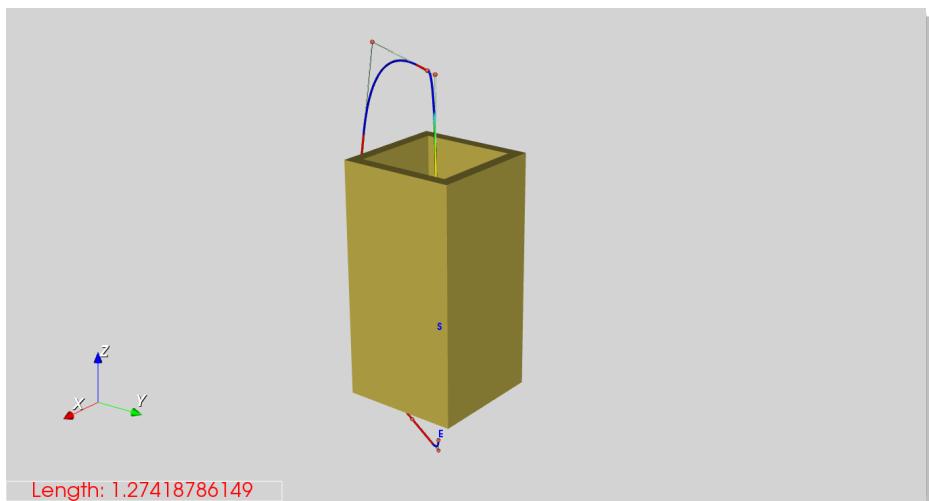
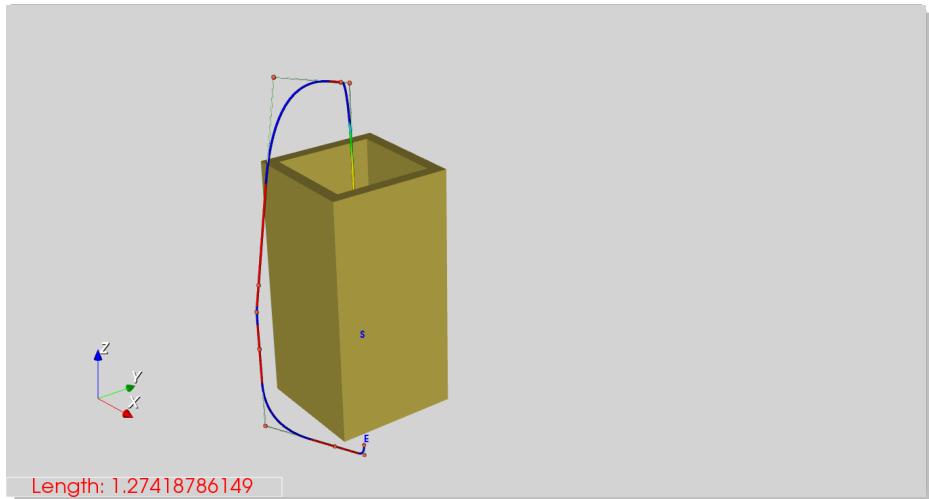


Figure 91.: Test 63; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 2; Meth. B; Post proc. X; Part. A.

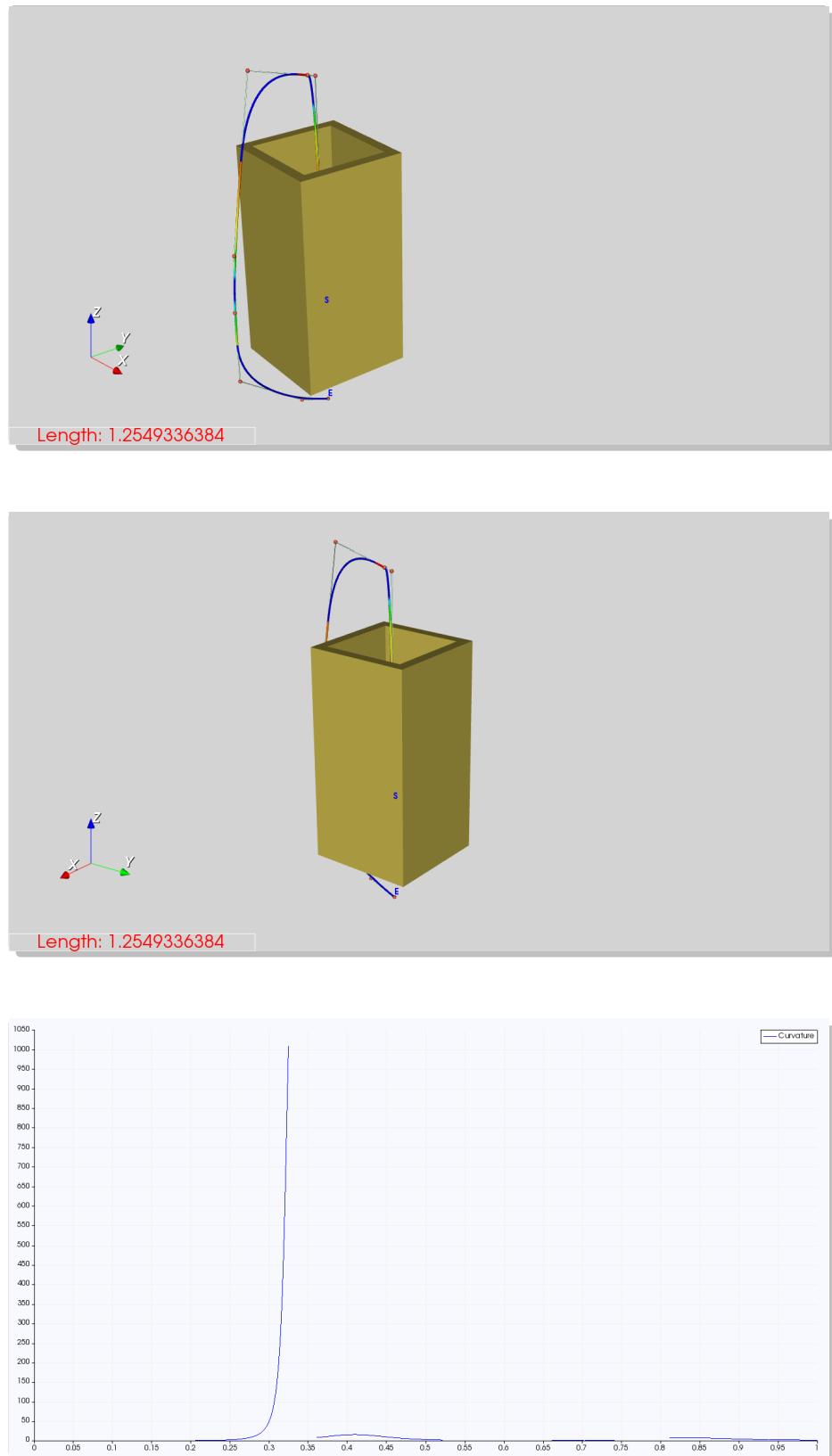


Figure 92.: Test 64; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 2; Meth. B; Post proc. ✓; Part. A.

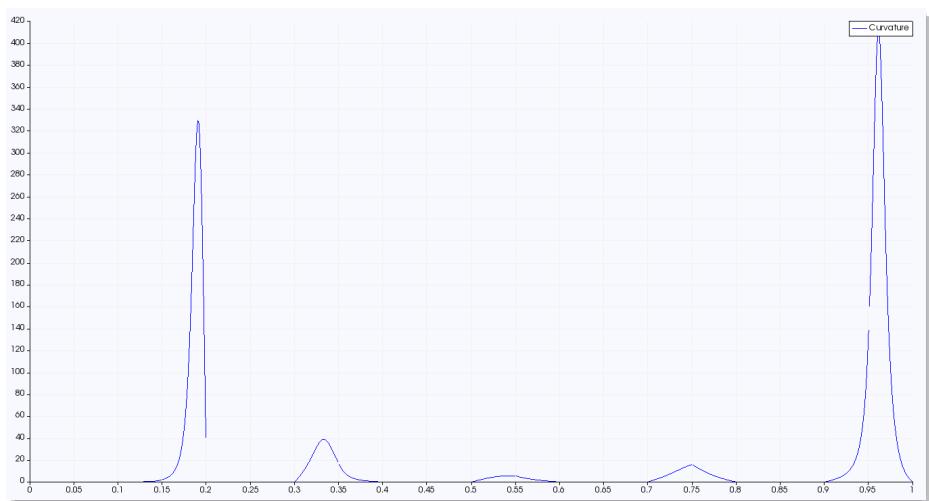
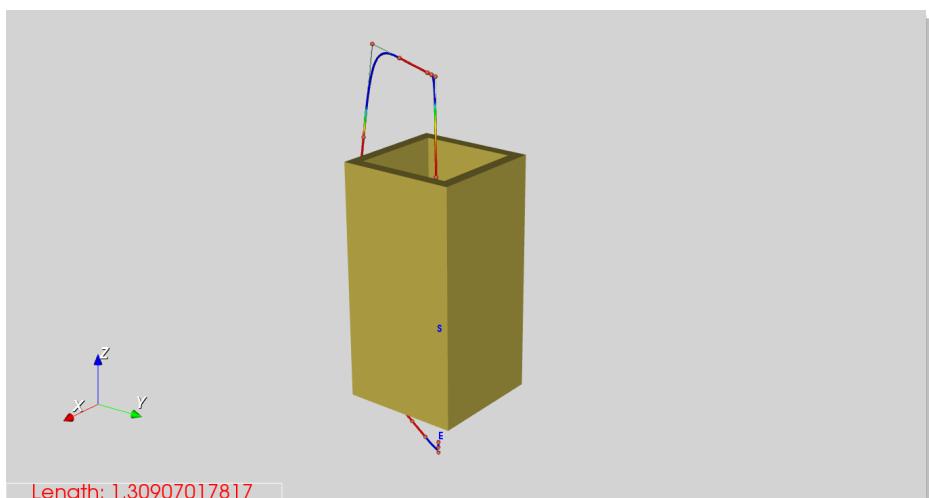
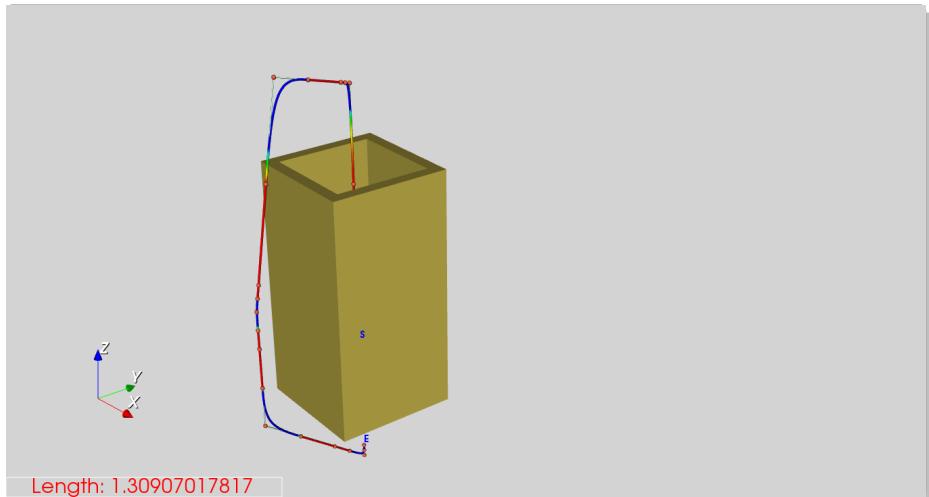


Figure 93.: Test 65; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 3; Meth. B; Post proc. X; Part. U.

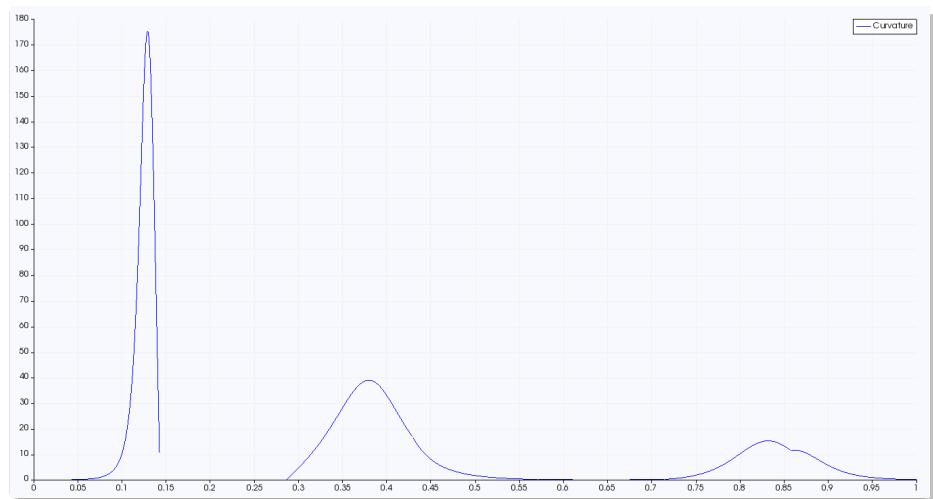
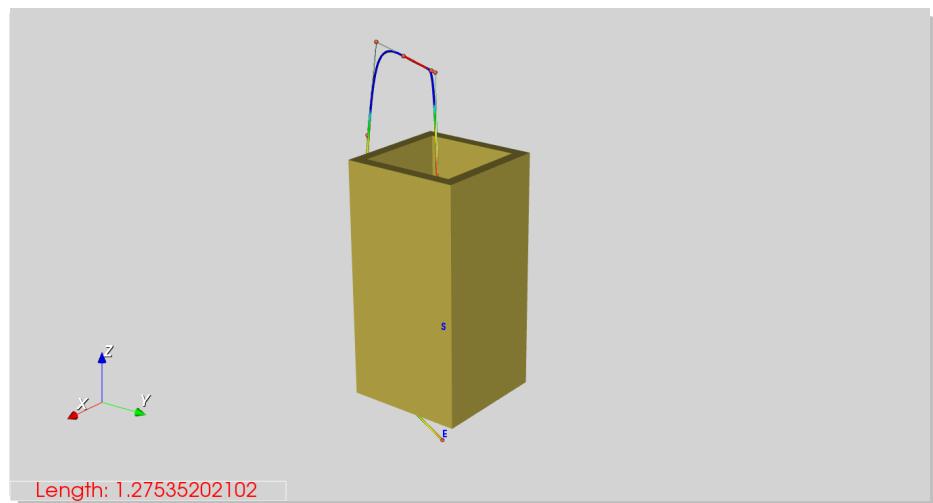
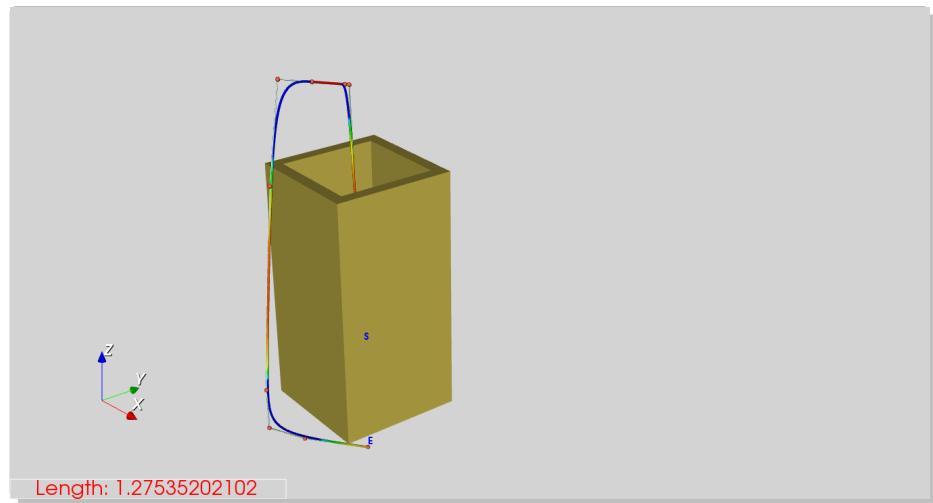


Figure 94.: Test 66; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 3; Meth. B; Post proc. ✓; Part. U.

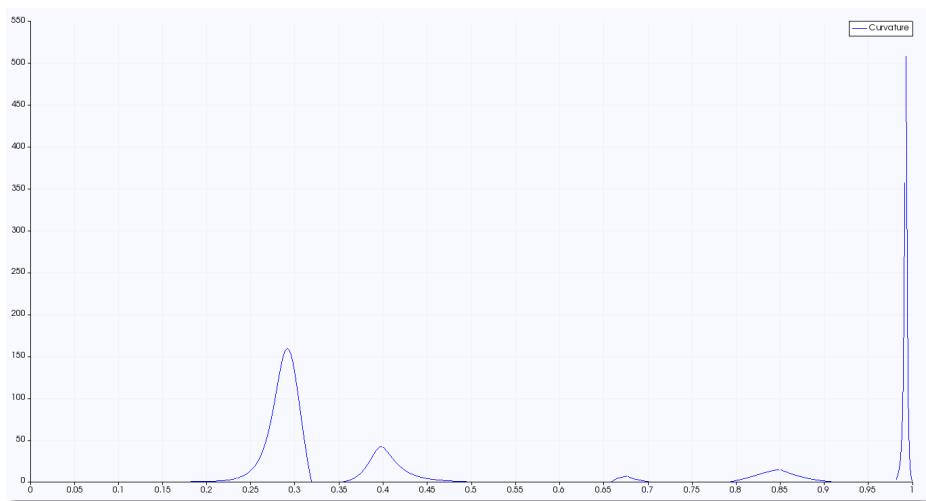
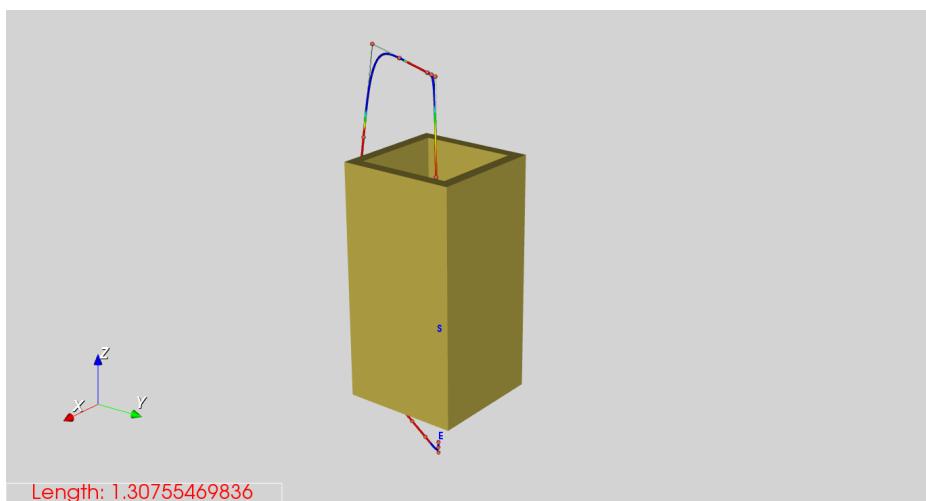
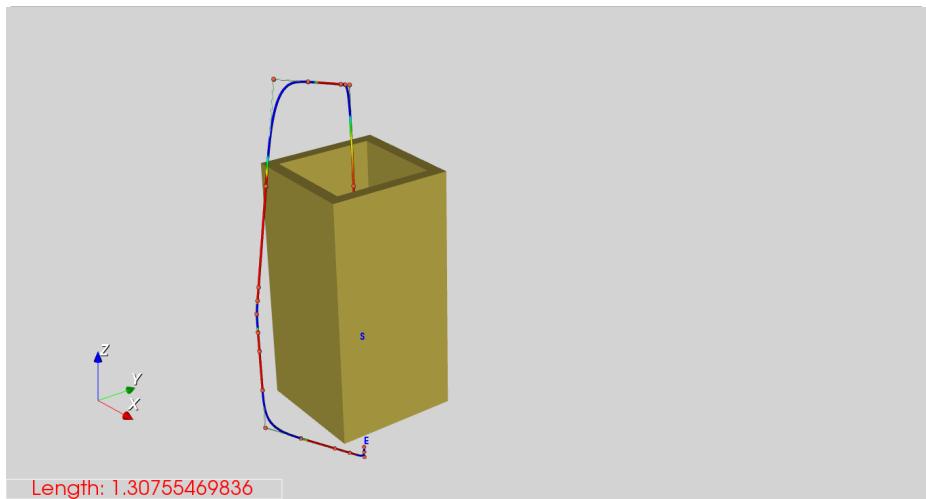


Figure 95.: Test 67; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 3; Meth. B; Post proc. X; Part. A.

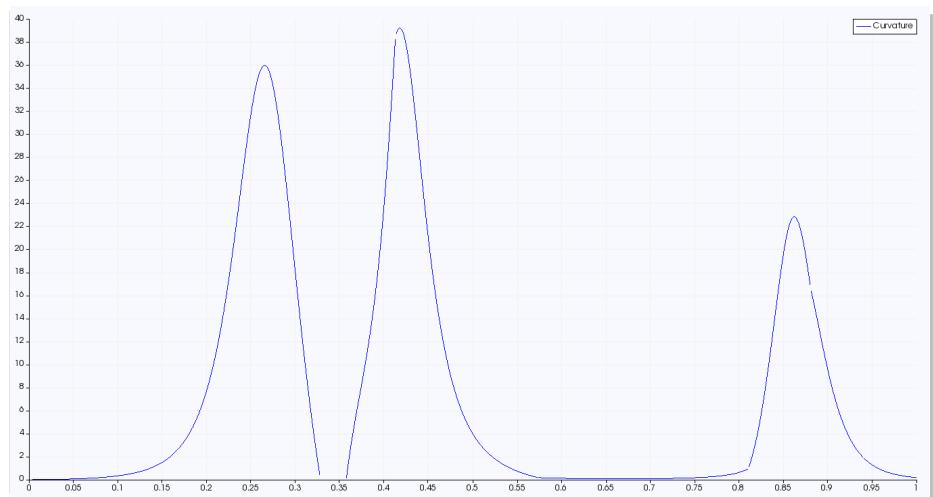
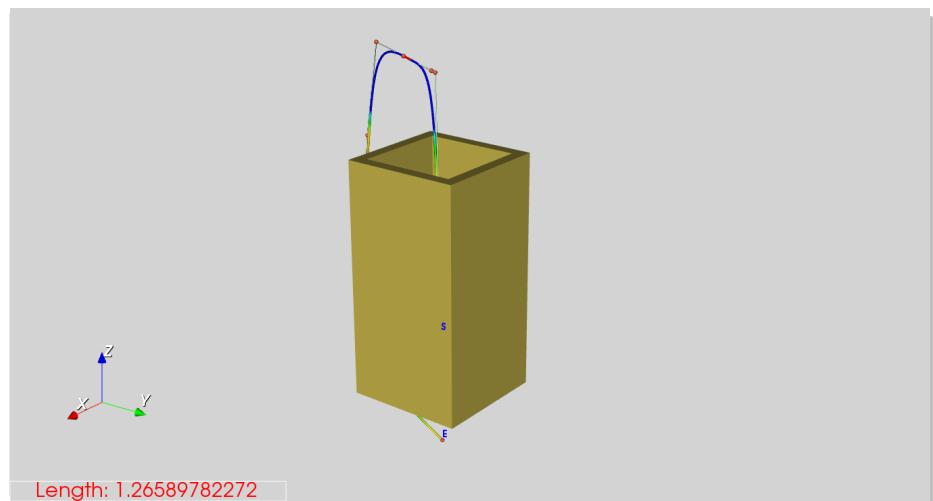
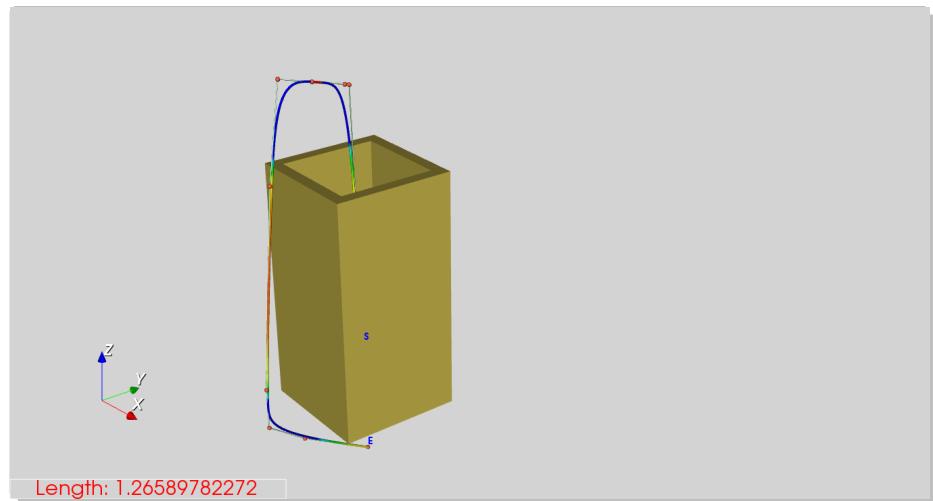


Figure 96.: Test 68; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 3; Meth. B; Post proc. ✓; Part. A.

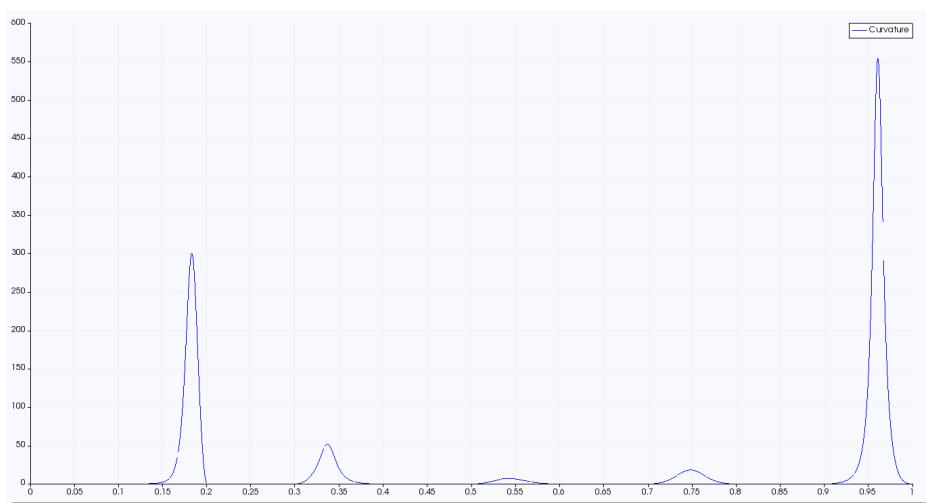
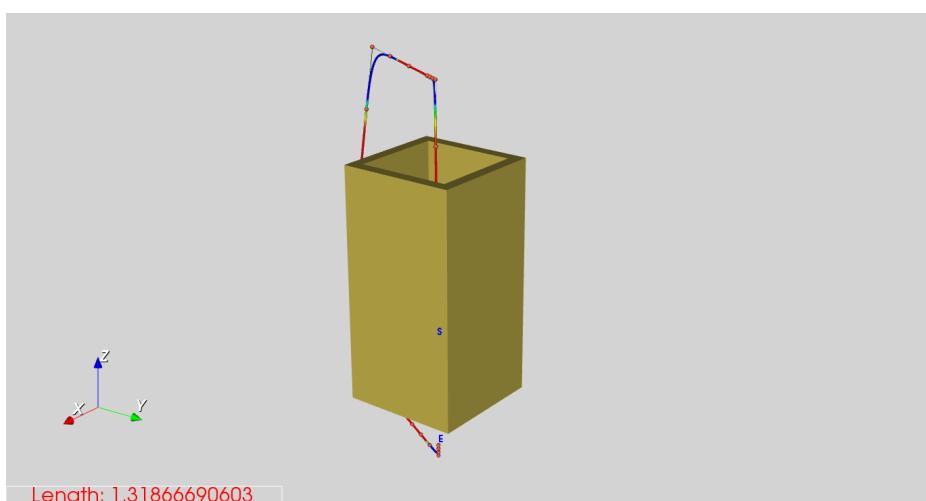
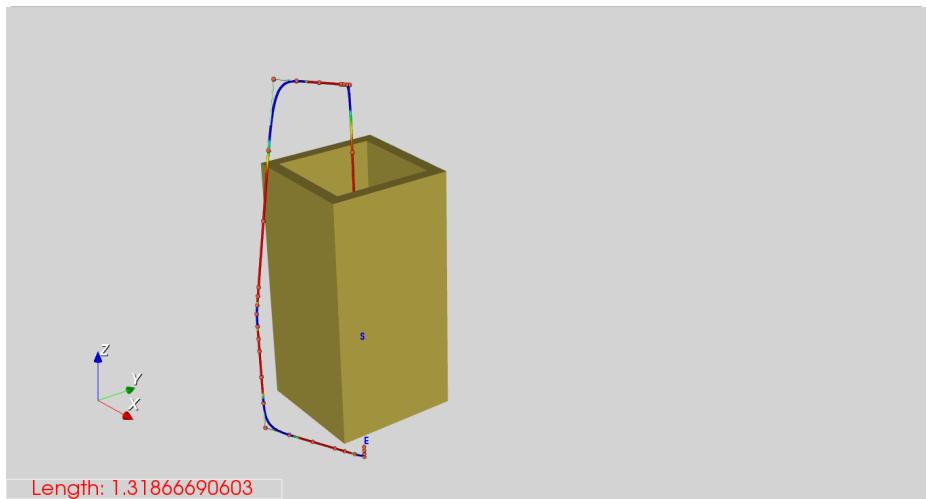


Figure 97.: Test 69; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 4; Meth. B; Post proc.  $\chi$ ; Part. U.

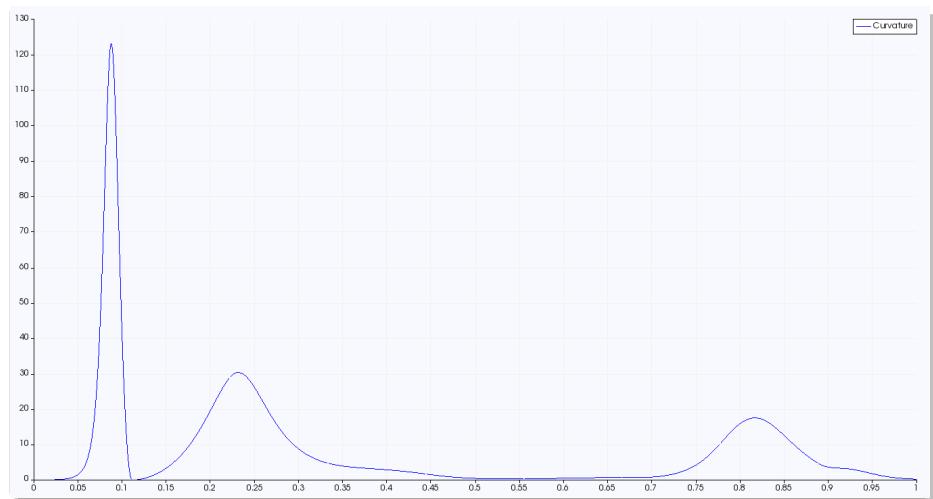
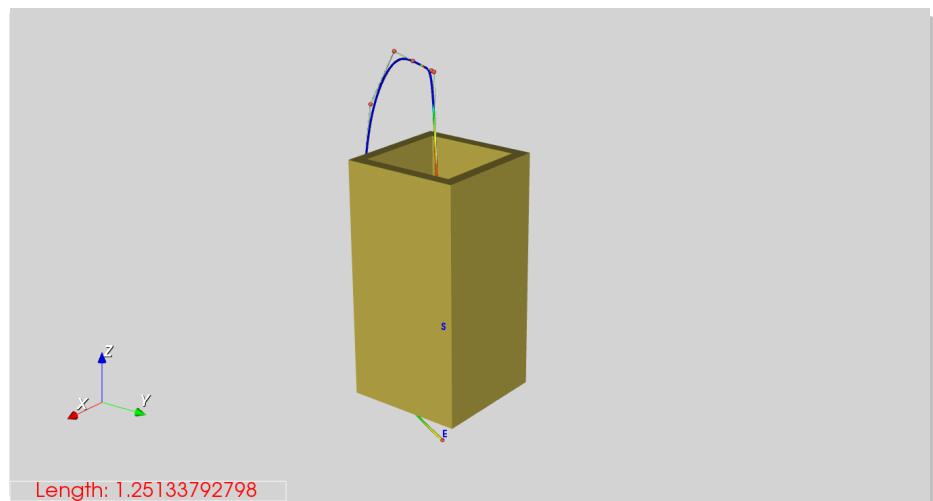
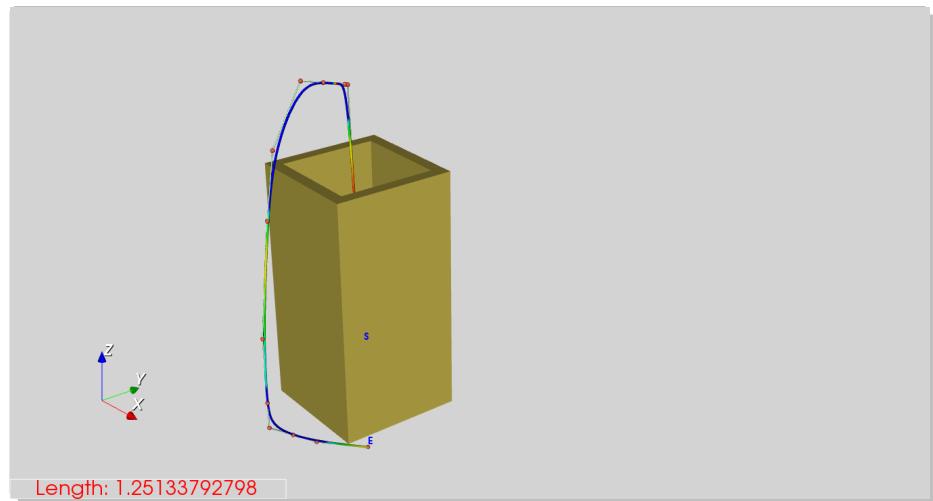


Figure 98.: Test 70; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 4; Meth. B; Post proc. ✓; Part. U.

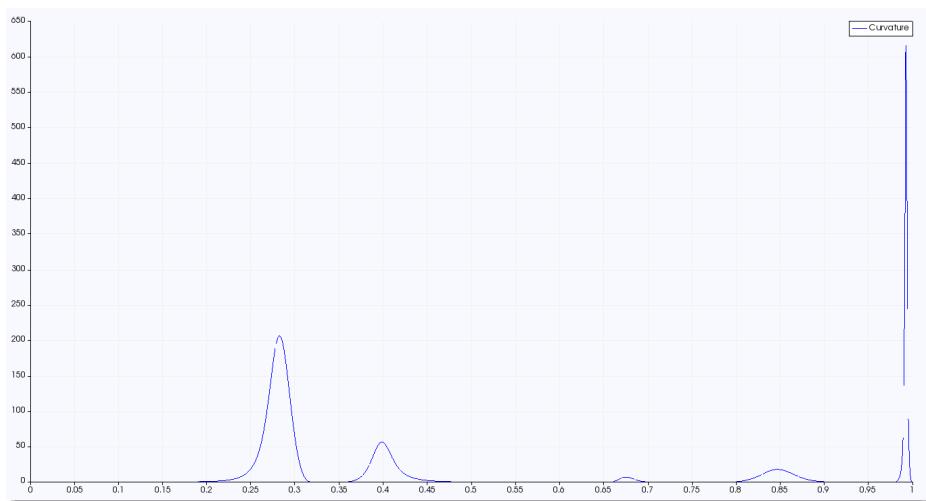
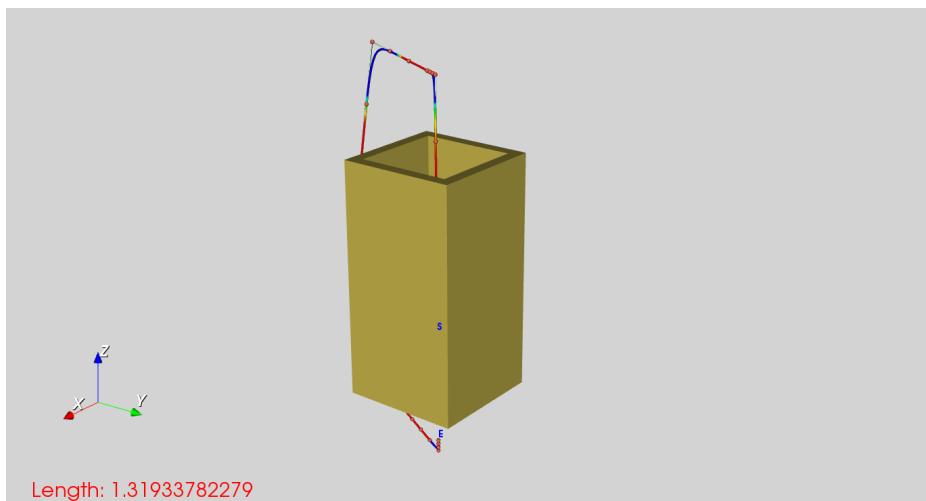
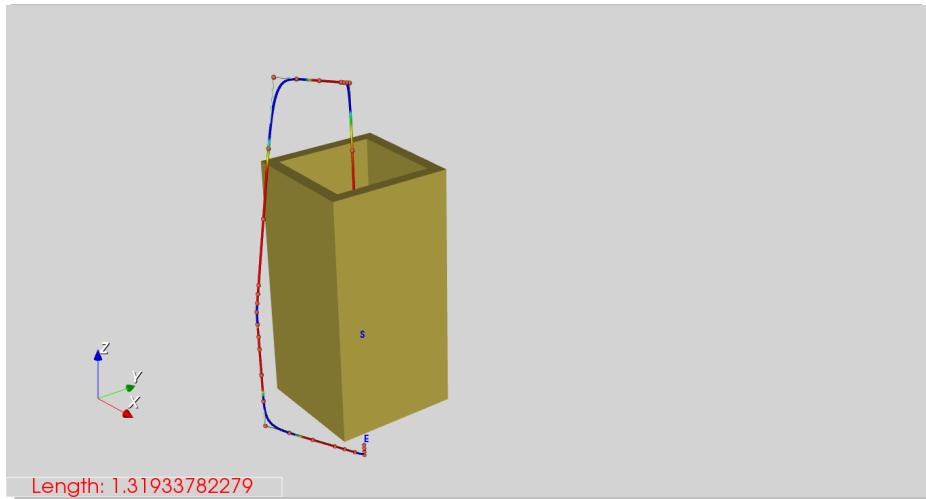


Figure 99.: Test 71; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 4; Meth. B; Post proc. X; Part. A.

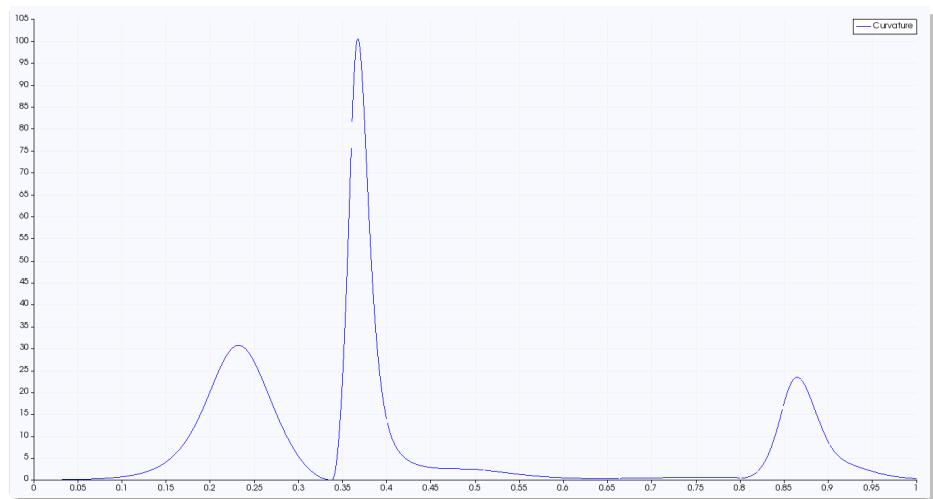
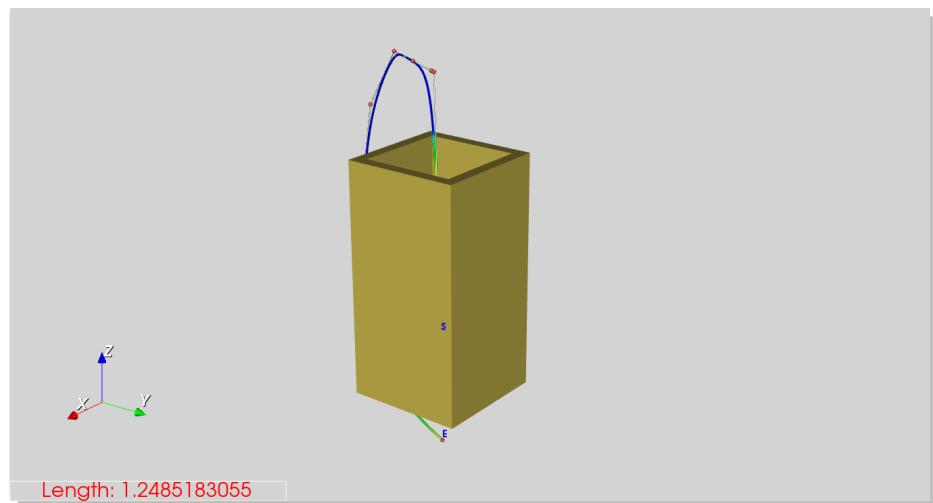
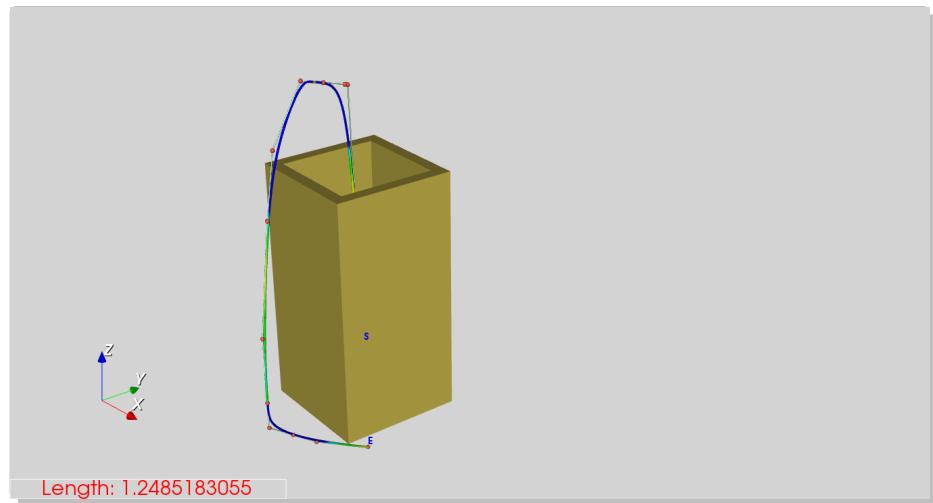


Figure 100.: Test 72; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 4; Meth. B; Post proc. ✓; Part. A.

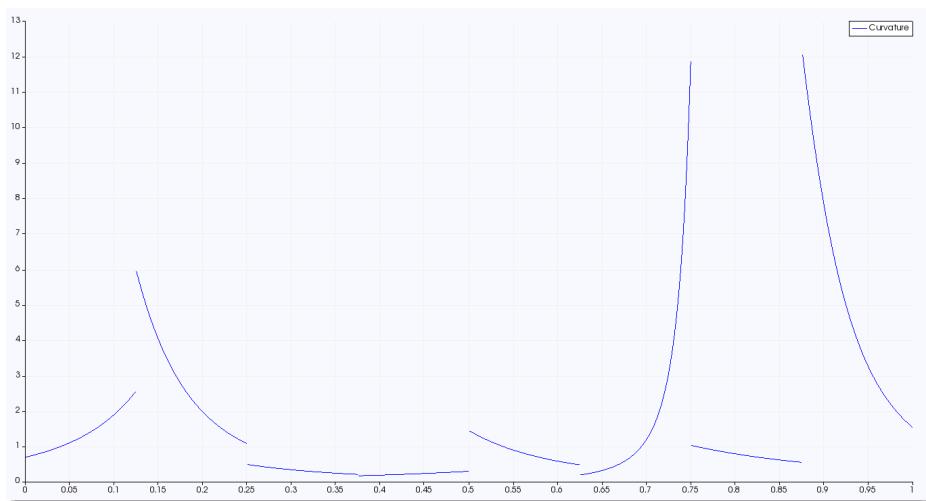
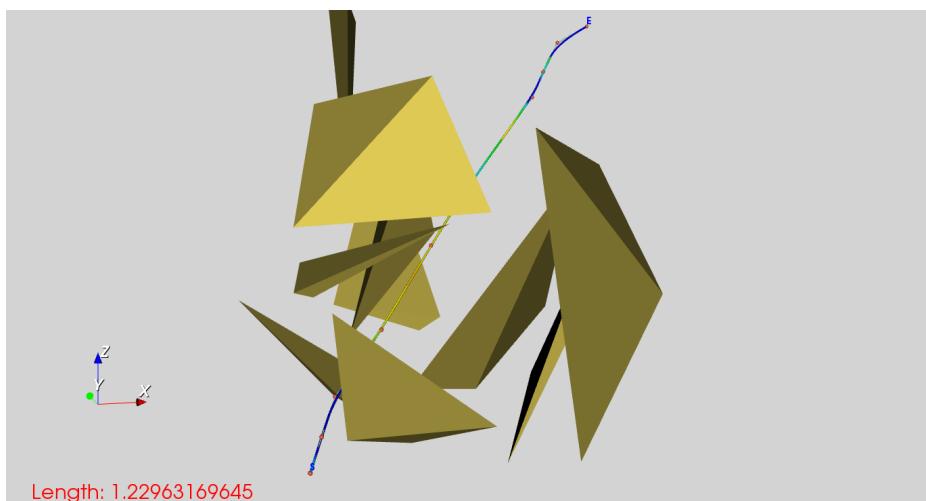
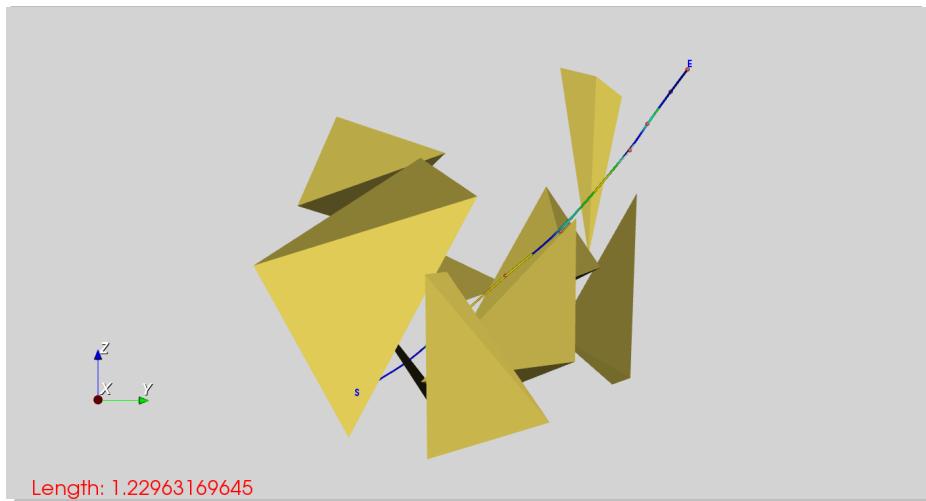


Figure 101.: Test 73; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 2; Meth. C; Part. U; Config. 1.

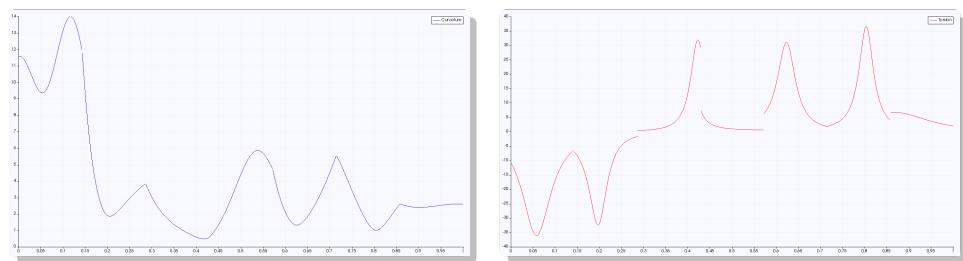
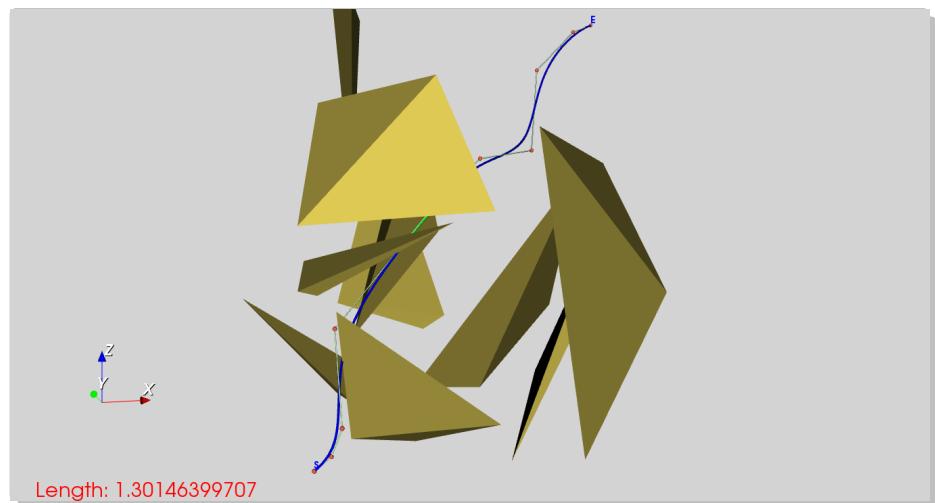
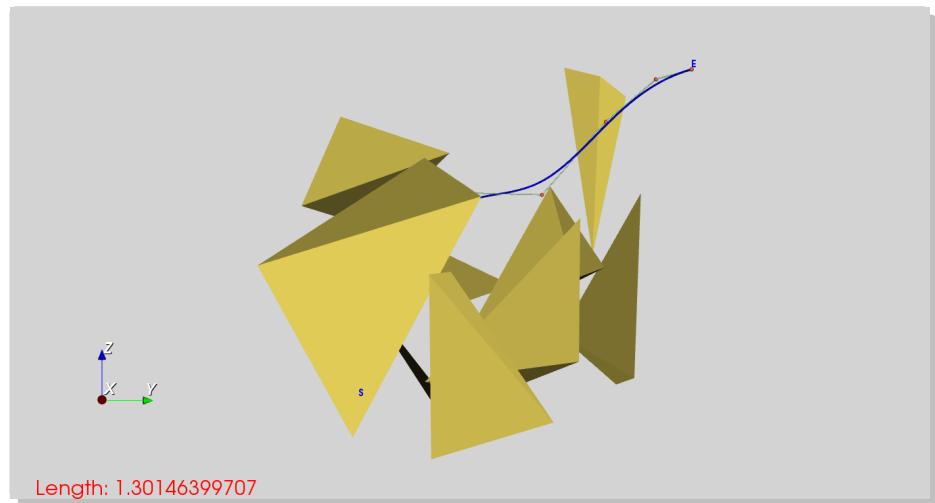


Figure 102.: Test 74; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 3; Meth. C; Part. U; Config. 1.

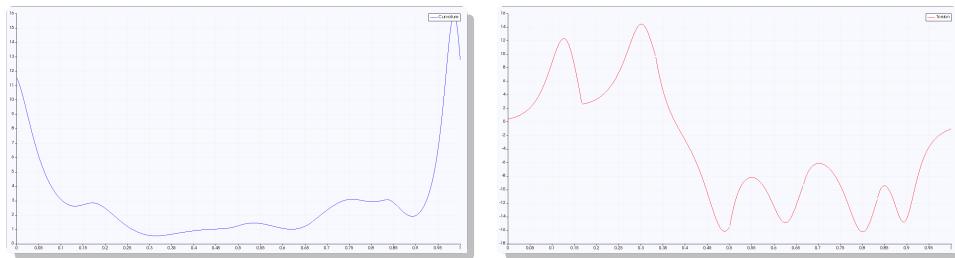
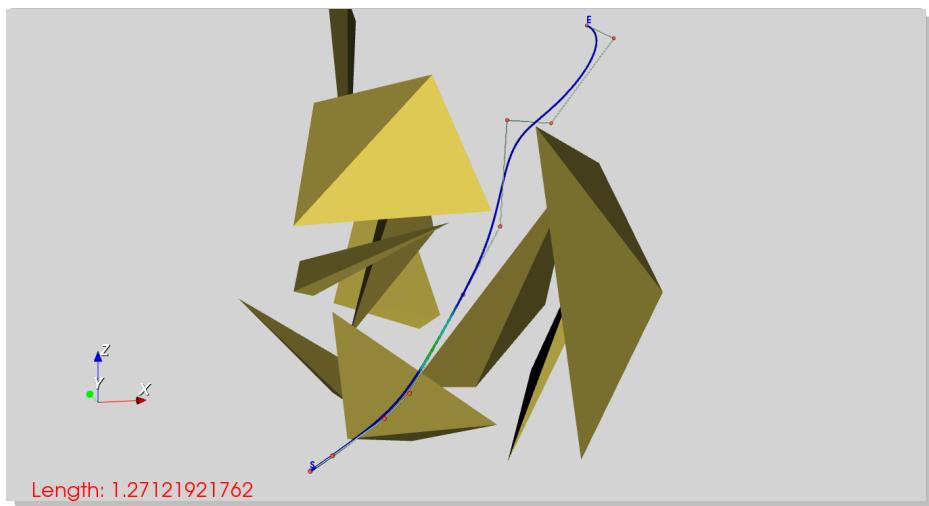
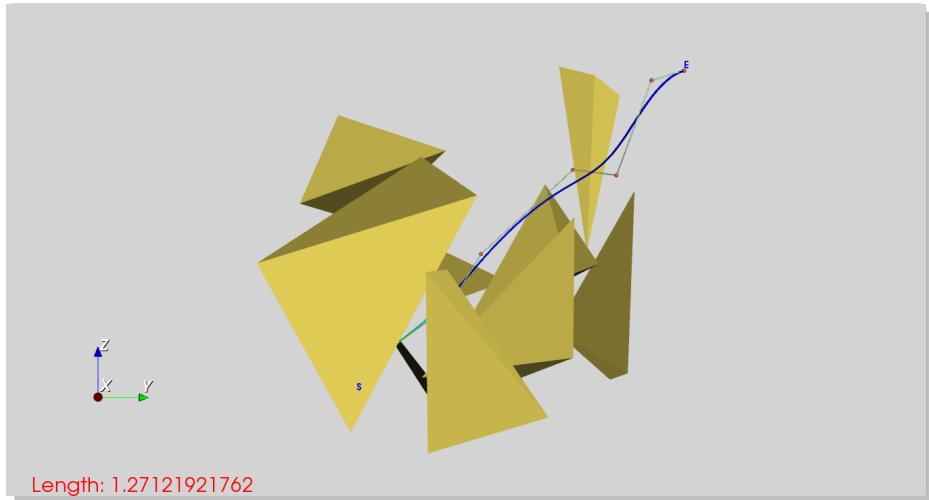


Figure 103.: Test 75; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 4; Meth. C; Part. U; Config. 1.

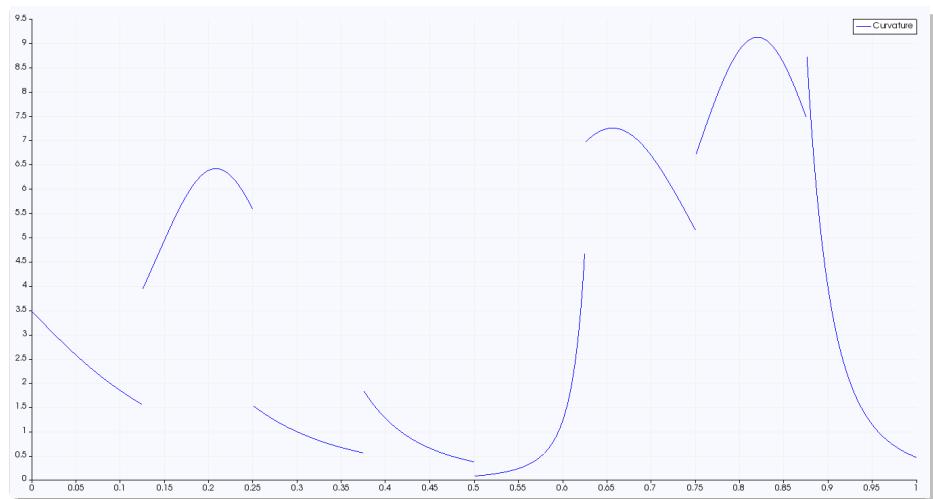
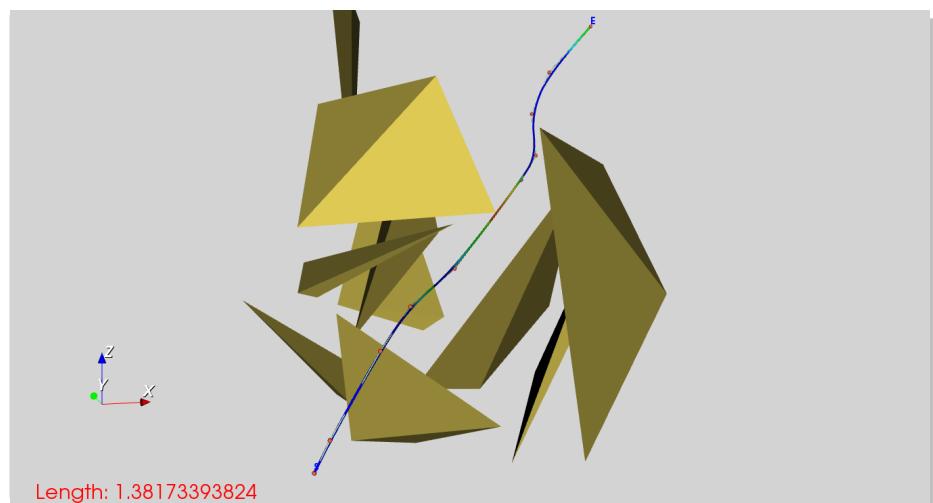
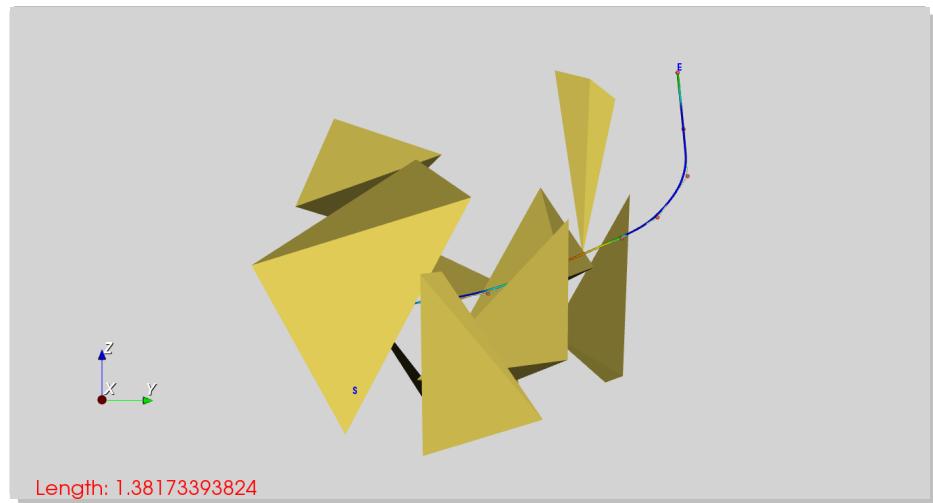


Figure 104.: Test 76; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 2; Meth. C; Part. U; Config. 2.

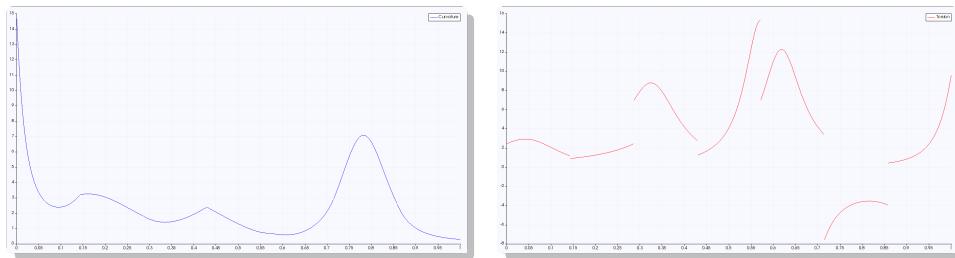
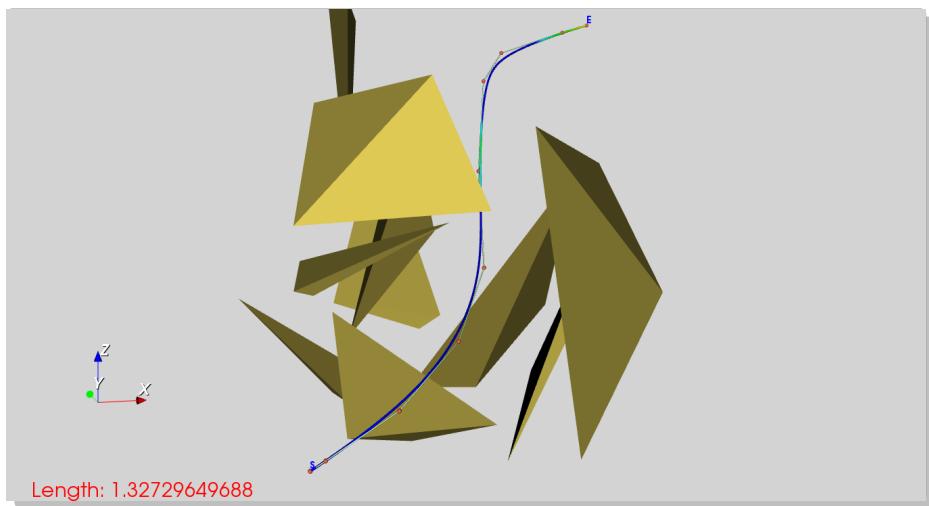
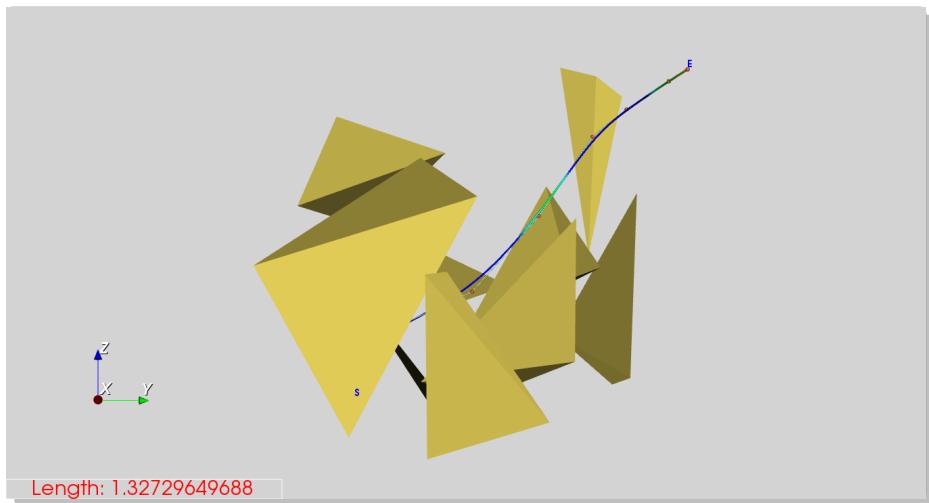


Figure 105.: Test 77; Scene 1;  $s \rightarrow e [0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 3; Meth. C; Part. U; Config. 2.

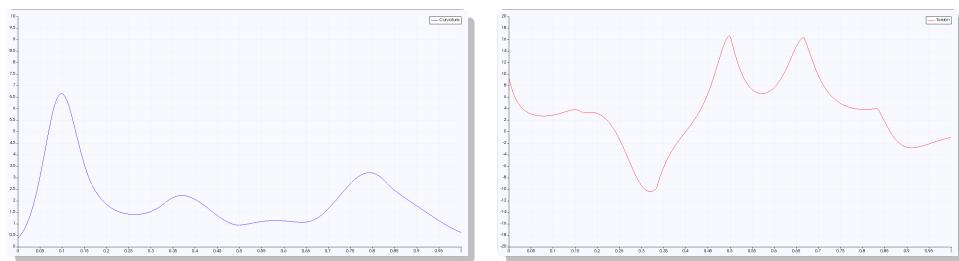
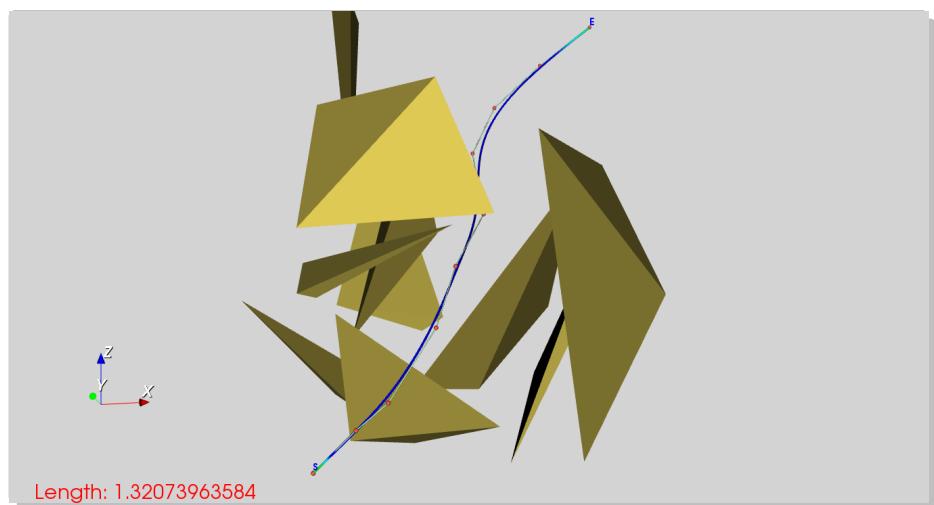
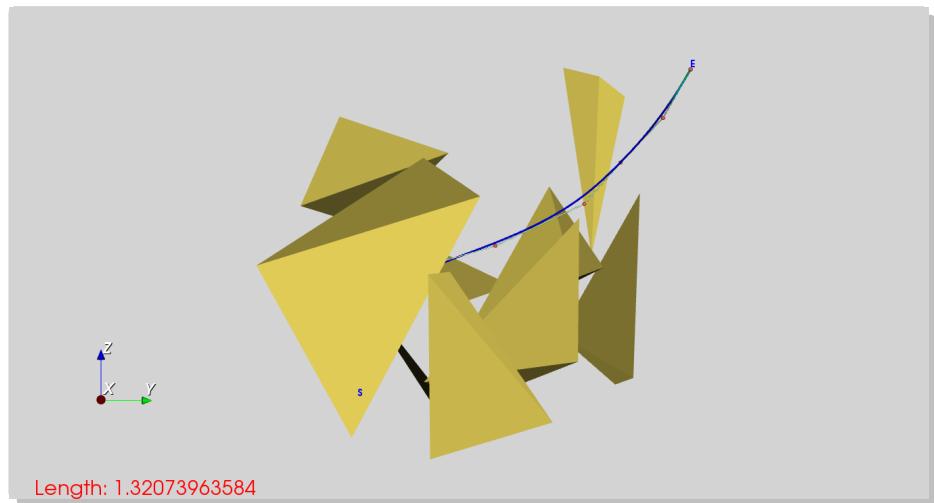


Figure 106.: Test 78; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 4; Meth. C; Part. U; Config. 2.

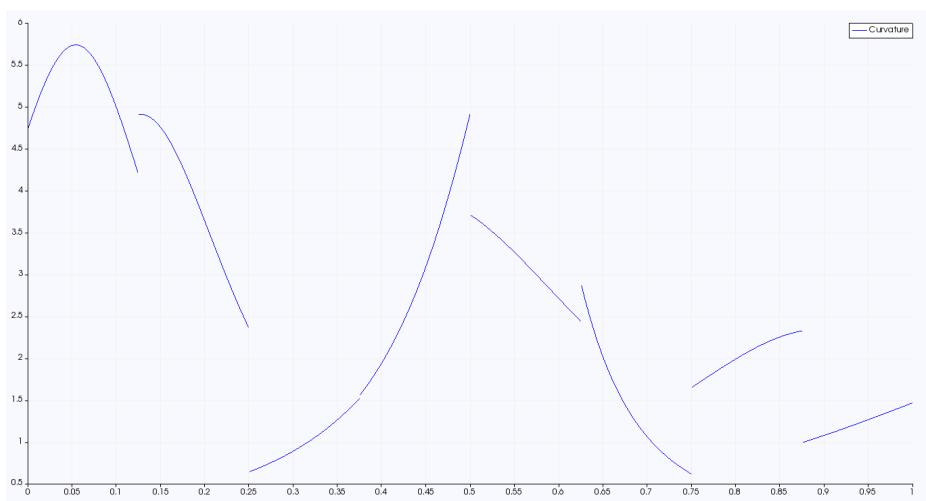
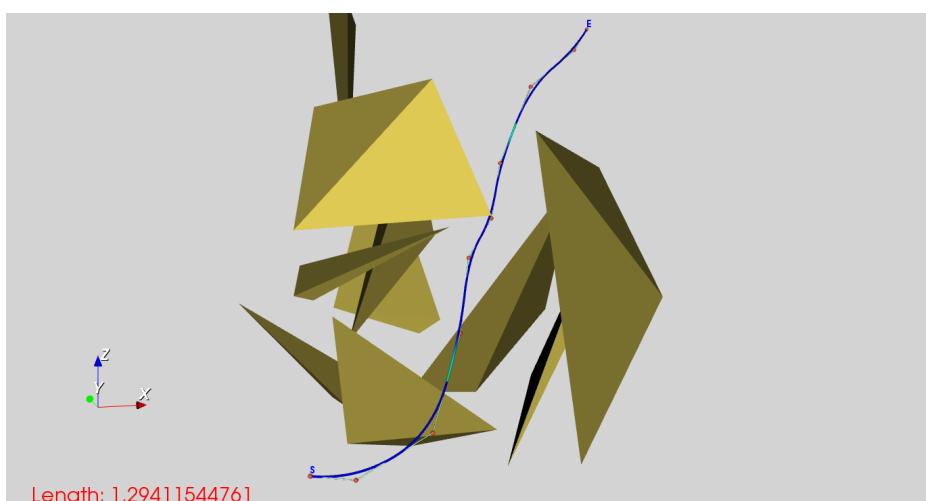
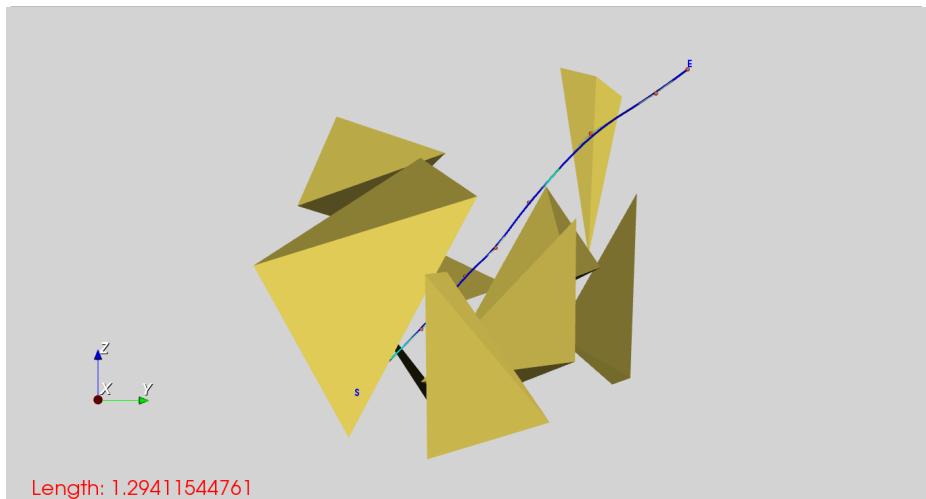


Figure 107.: Test 79; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 2; Meth. C; Part. U; Config. 3.

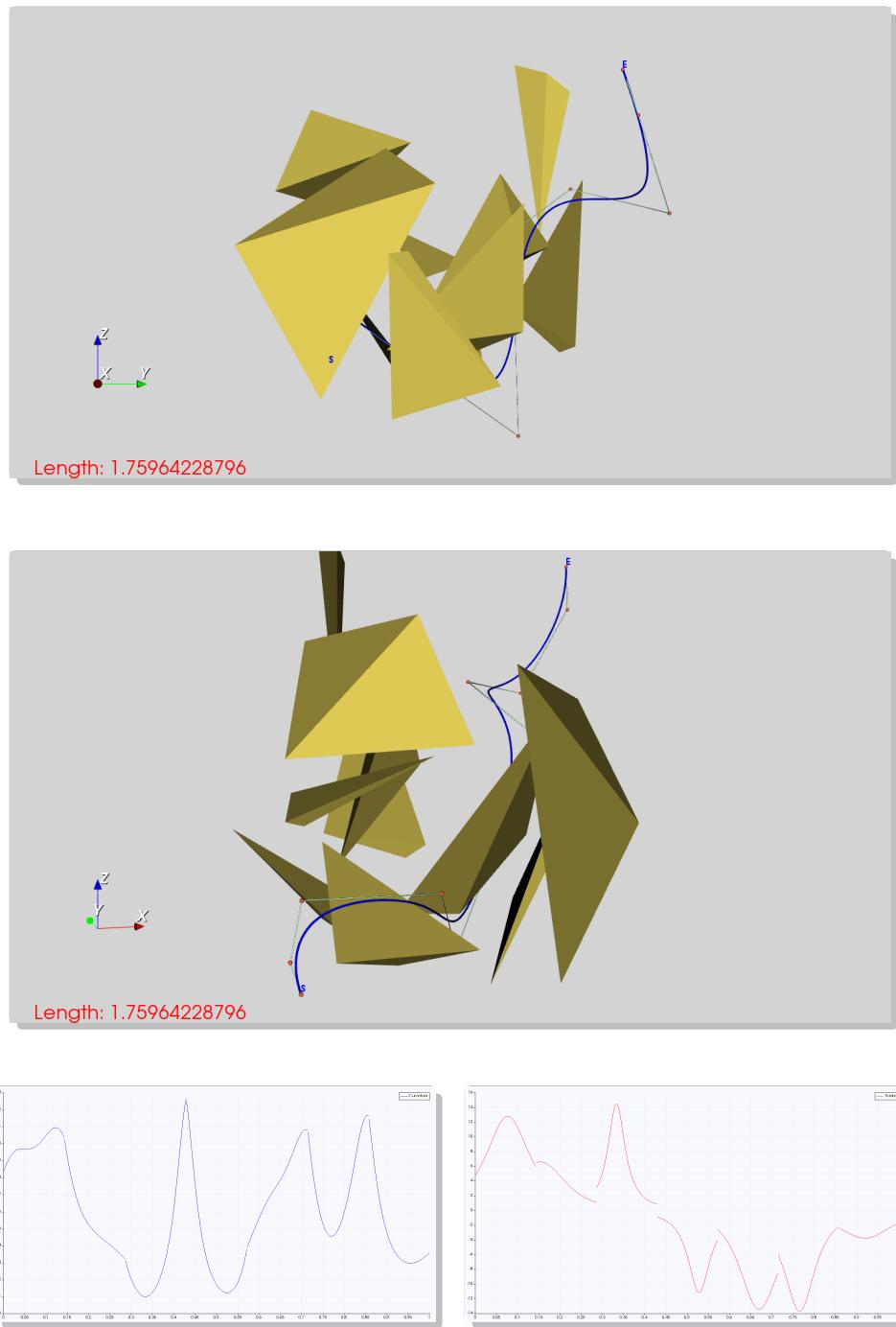


Figure 108.: Test 8o; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 3; Meth. C; Part. U; Config. 3.

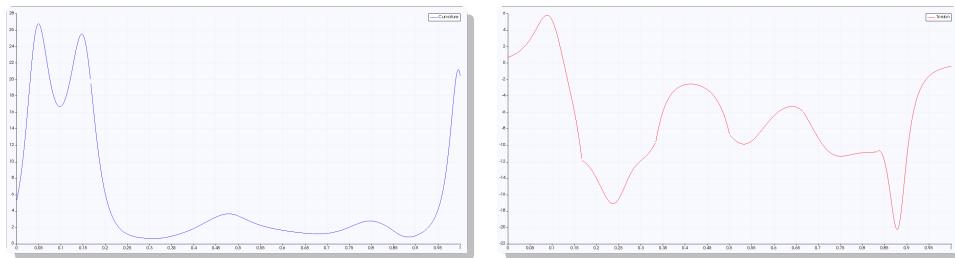
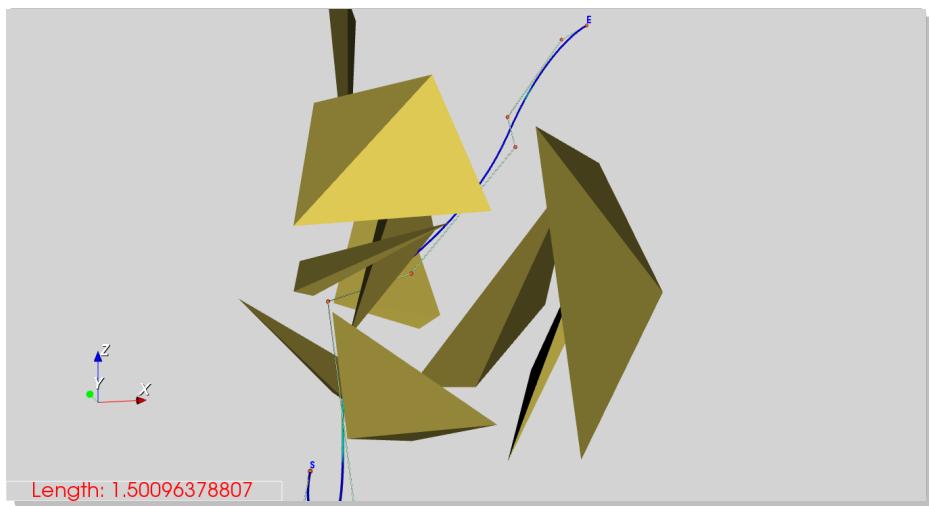
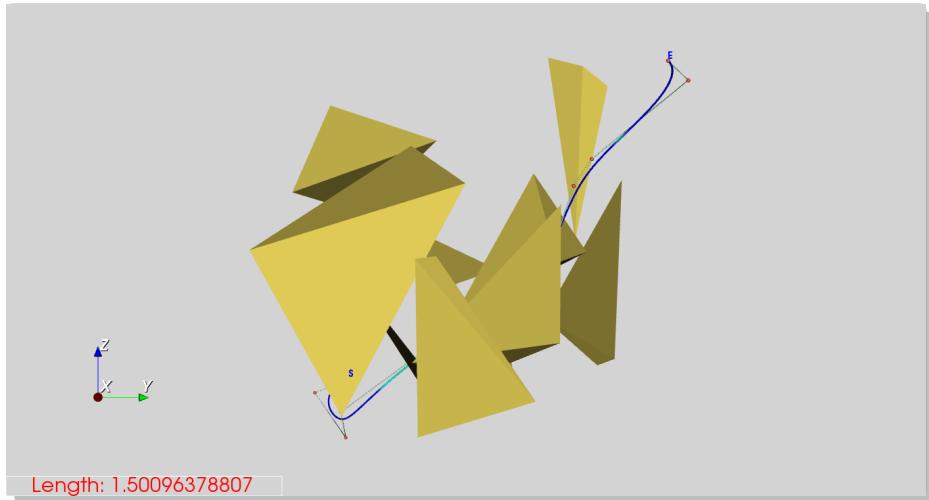


Figure 109.: Test 81; Scene 1;  $s \rightarrow e$   $[0.2, 0.2, 0.2] \rightarrow [0.9, 0.9, 0.9]$ ; Deg. 4; Meth. C; Part. U; Config. 3.

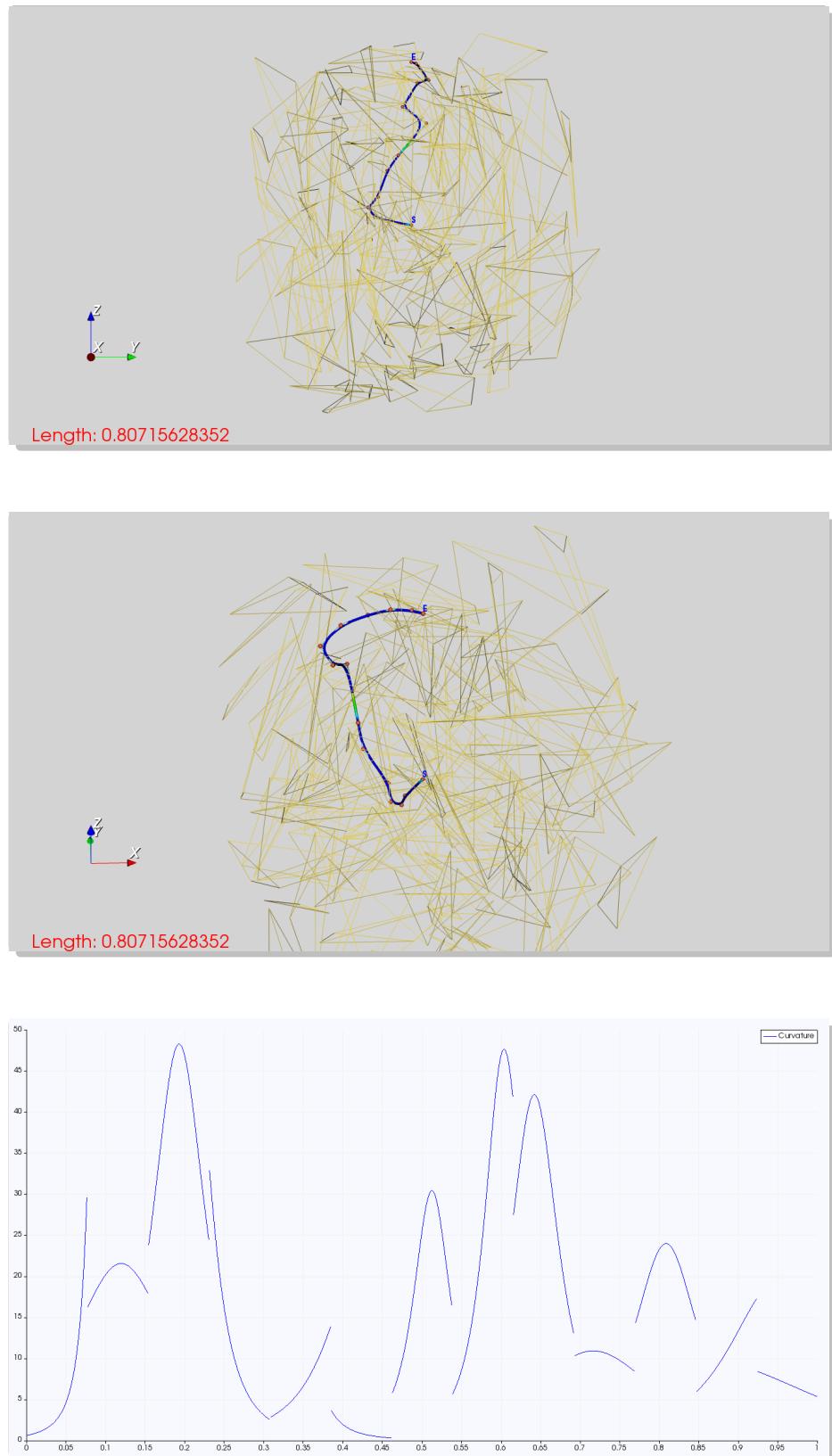


Figure 110.: Test 82; Scene 2;  $s \rightarrow e$   $[0.5, 0.5, 0.5] \rightarrow [0.5, 0.5, 0.95]$ ; Deg. 2; Meth. C; Part. U; Config. 1.

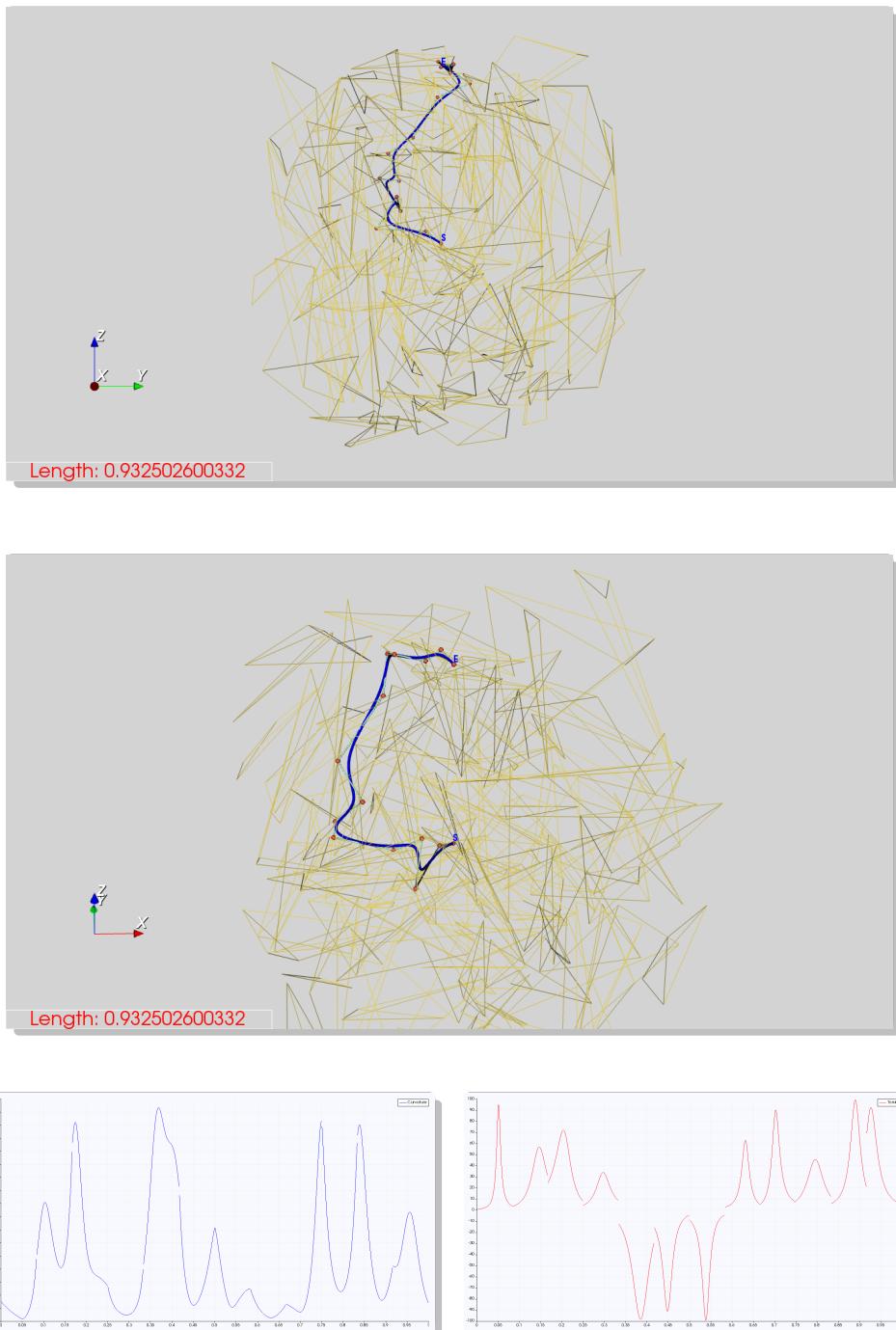


Figure 111.: Test 83; Scene 2;  $s \rightarrow e$   $[0.5, 0.5, 0.5] \rightarrow [0.5, 0.5, 0.95]$ ; Deg. 3; Meth. C; Part. U; Config. 1.



Figure 112.: Test 84; Scene 2;  $s \rightarrow e$   $[0.5, 0.5, 0.5] \rightarrow [0.5, 0.5, 0.95]$ ; Deg. 4; Meth. C; Part. U; Config. 1.

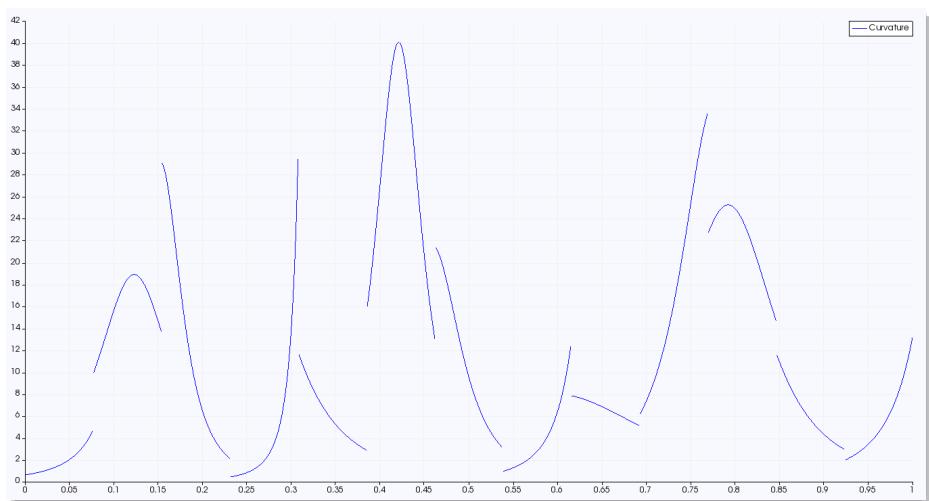
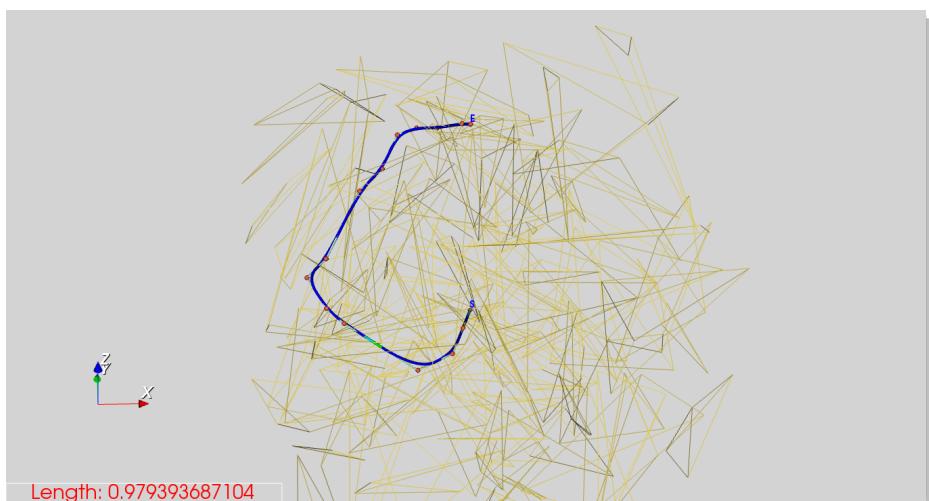
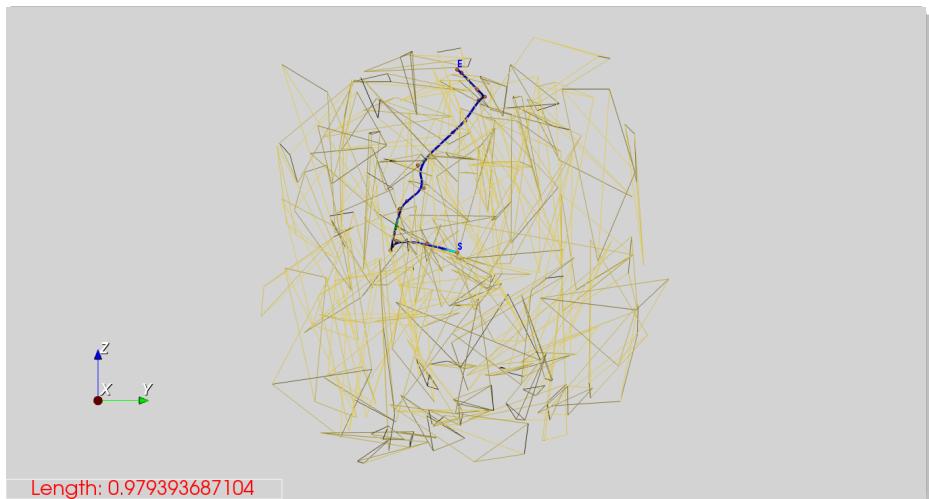


Figure 113.: Test 85; Scene 2;  $s \rightarrow e$   $[0.5, 0.5, 0.5] \rightarrow [0.5, 0.5, 0.95]$ ; Deg. 2; Meth. C; Part. U; Config. 2.

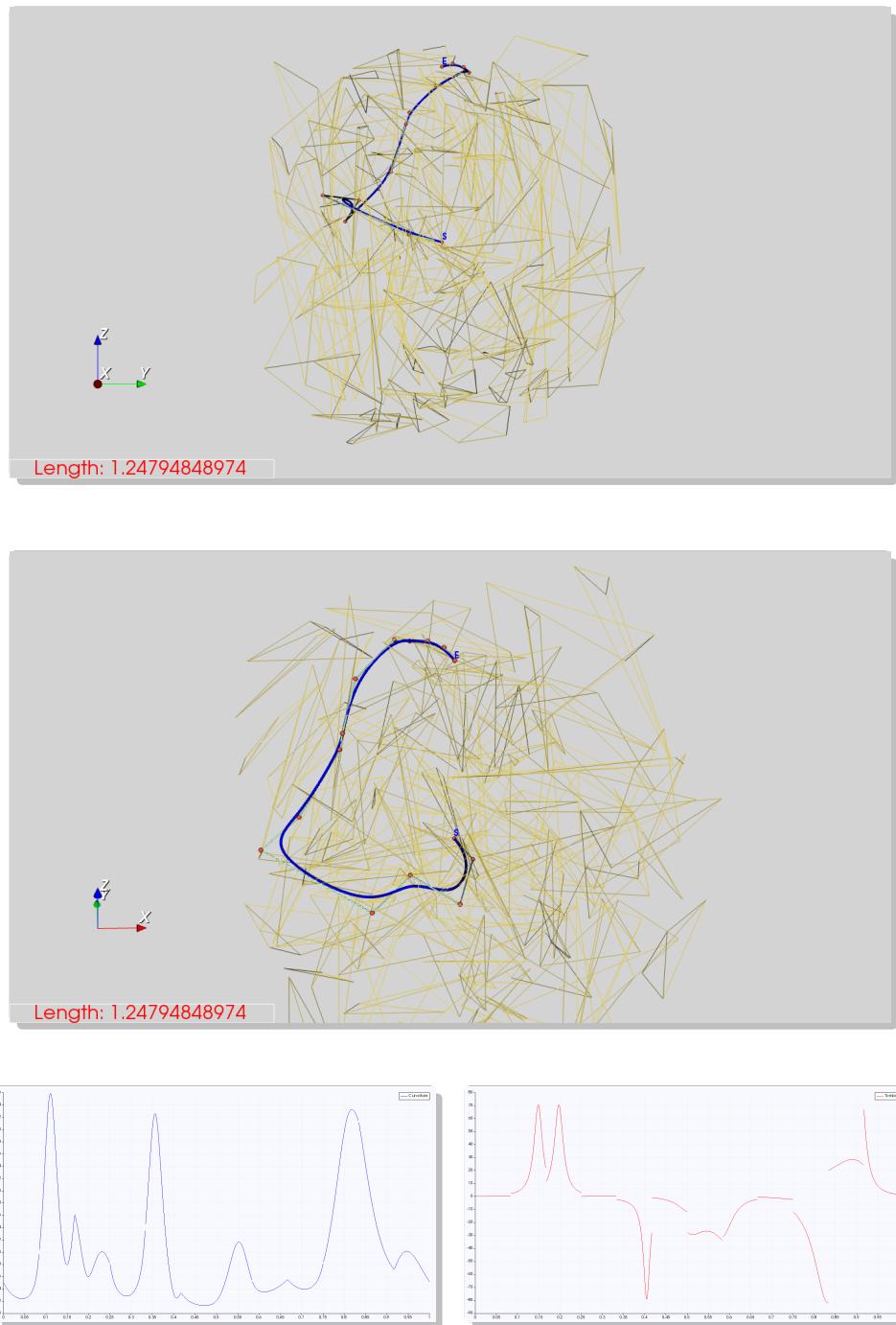


Figure 114.: Test 86; Scene 2;  $s \rightarrow e$   $[0.5, 0.5, 0.5] \rightarrow [0.5, 0.5, 0.95]$ ; Deg. 3; Meth. C; Part. U; Config. 2.

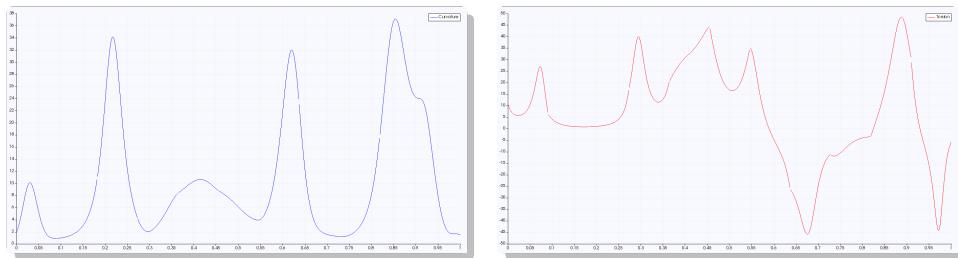


Figure 115.: Test 87; Scene 2;  $s \rightarrow e$   $[0.5, 0.5, 0.5] \rightarrow [0.5, 0.5, 0.95]$ ; Deg. 4; Meth. C; Part. U; Config. 2.

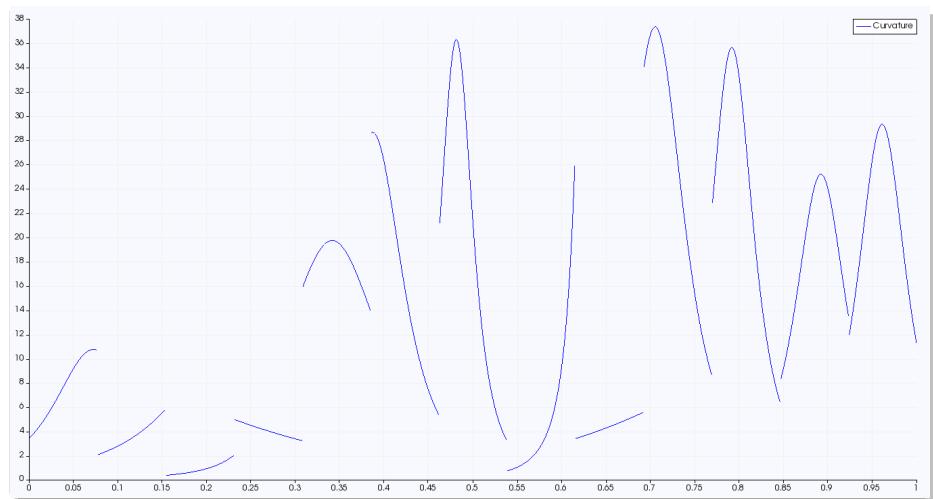
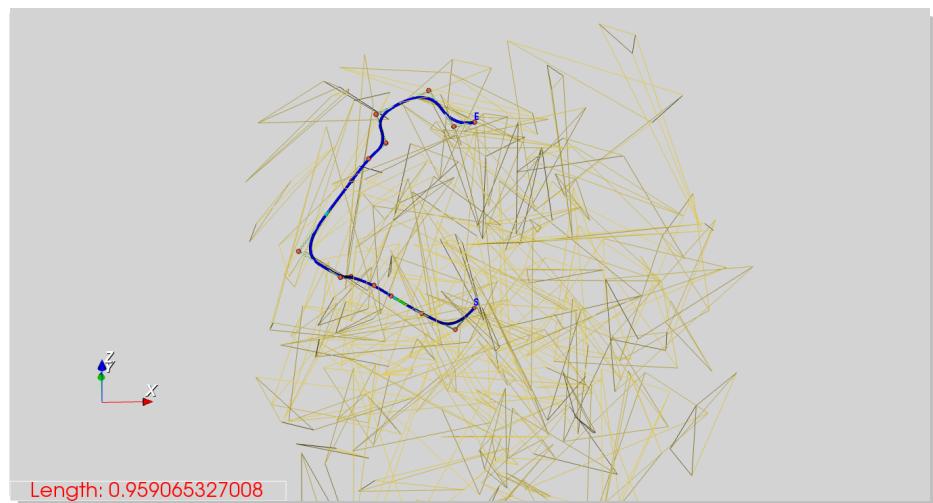
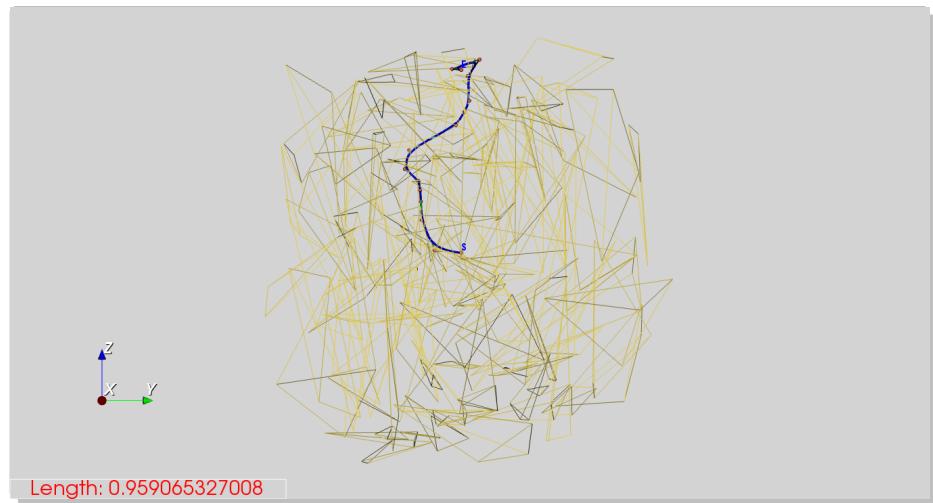


Figure 116.: Test 88; Scene 2;  $s \rightarrow e$   $[0.5, 0.5, 0.5] \rightarrow [0.5, 0.5, 0.95]$ ; Deg. 2; Meth. C; Part. U; Config. 3.

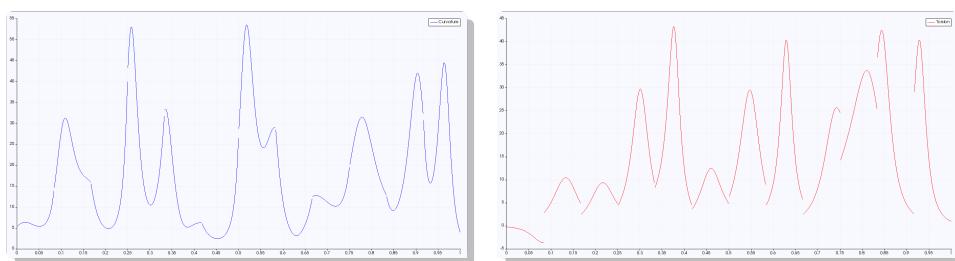
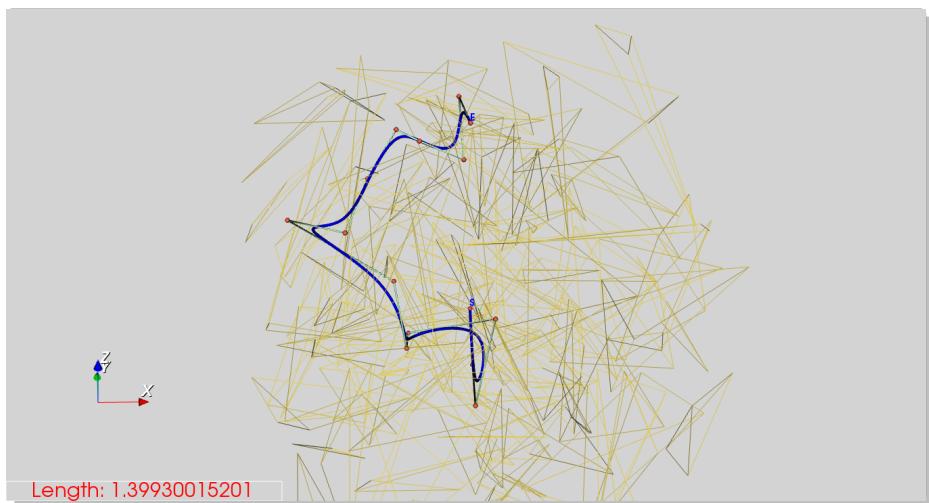
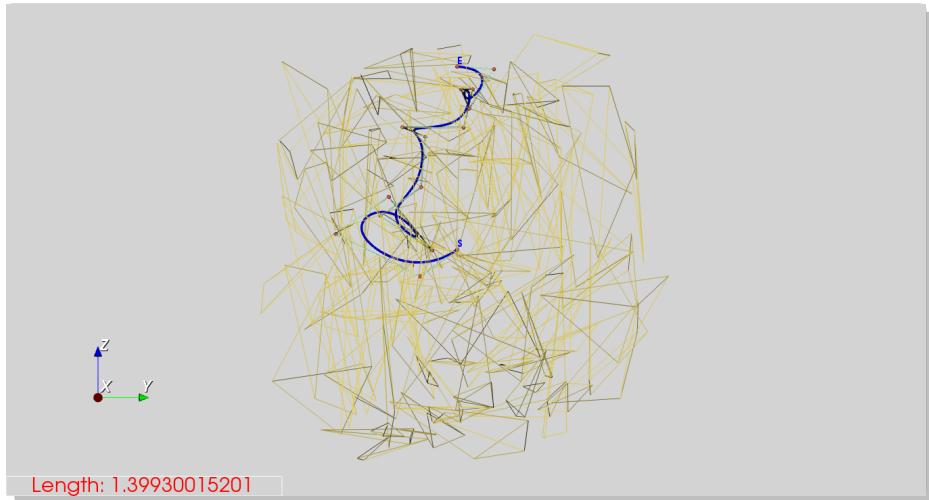


Figure 117.: Test 89; Scene 2;  $s \rightarrow e$   $[0.5, 0.5, 0.5] \rightarrow [0.5, 0.5, 0.95]$ ; Deg. 3; Meth. C; Part. U; Config. 3.

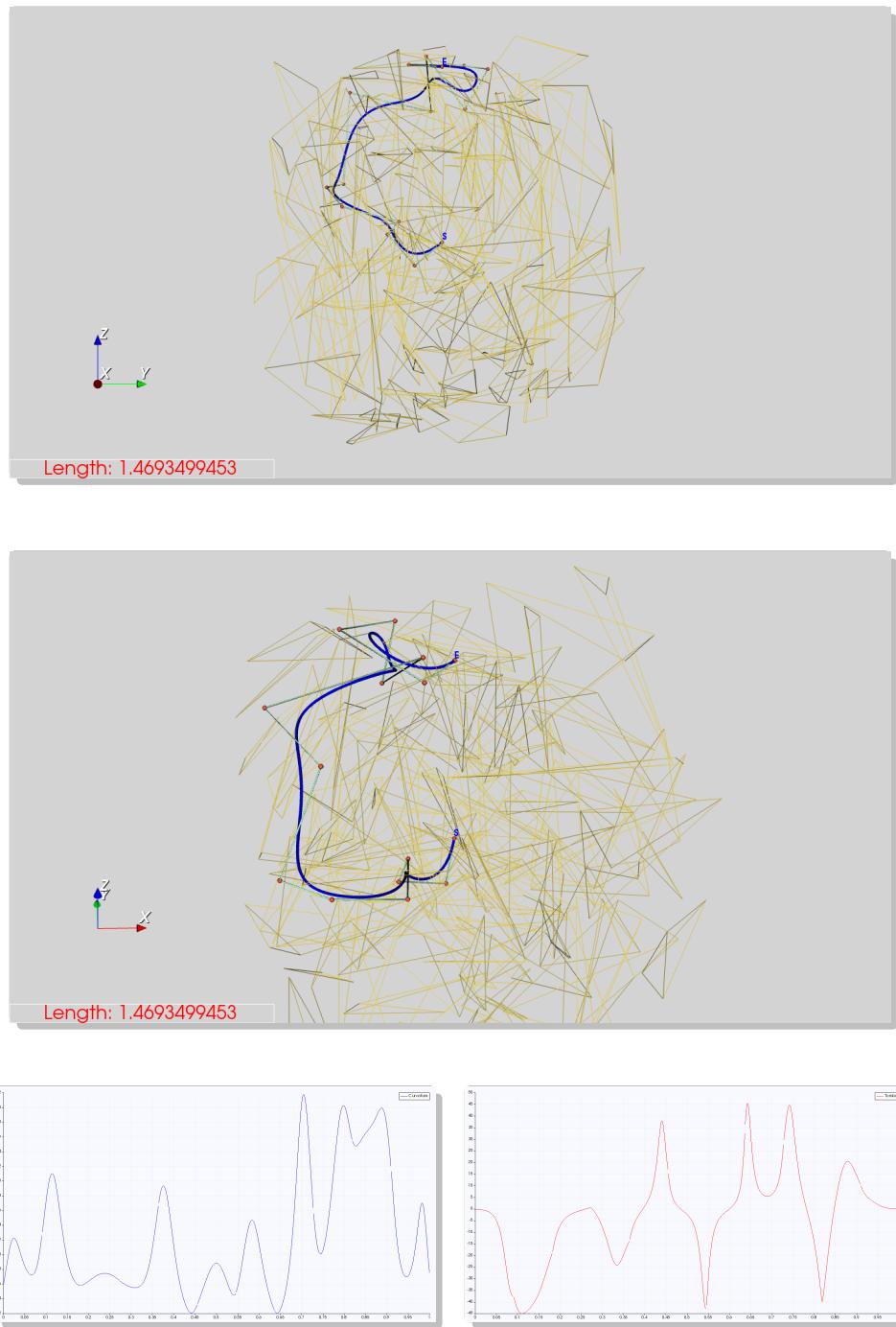


Figure 118.: Test 90; Scene 2;  $s \rightarrow e$   $[0.5, 0.5, 0.5] \rightarrow [0.5, 0.5, 0.95]$ ; Deg. 4; Meth. C; Part. U; Config. 3.

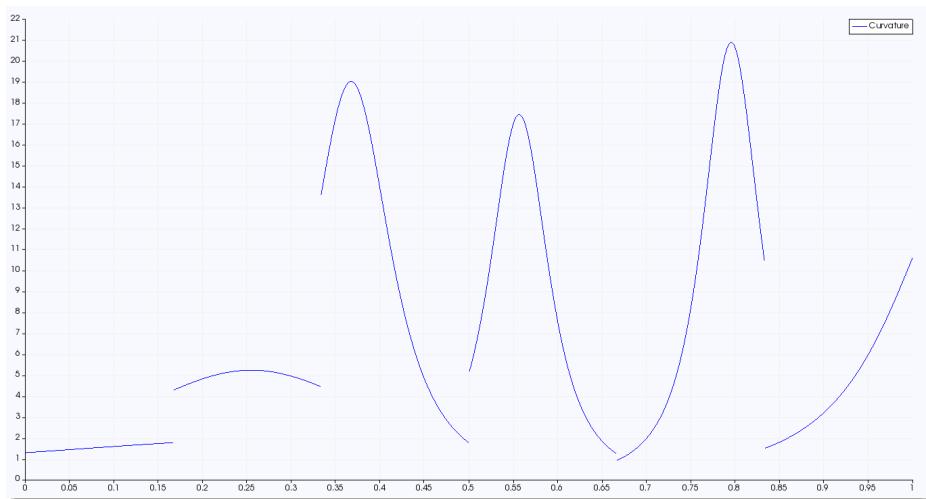
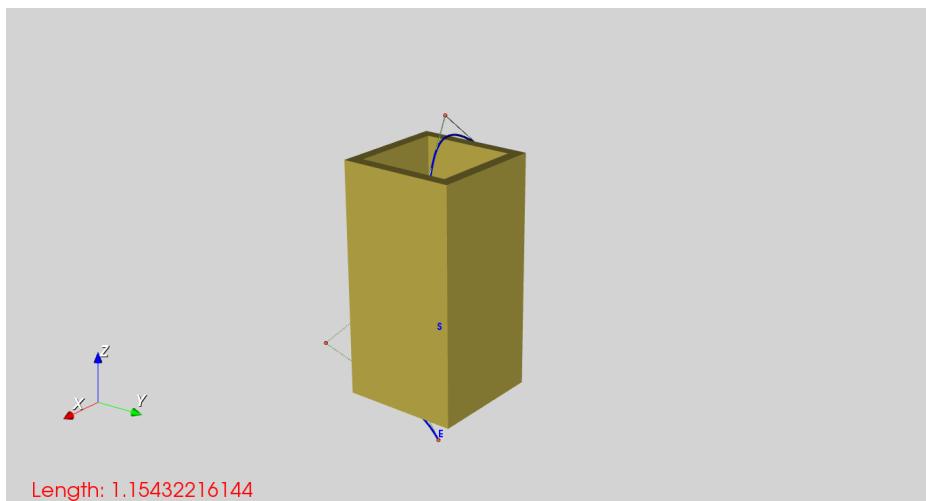
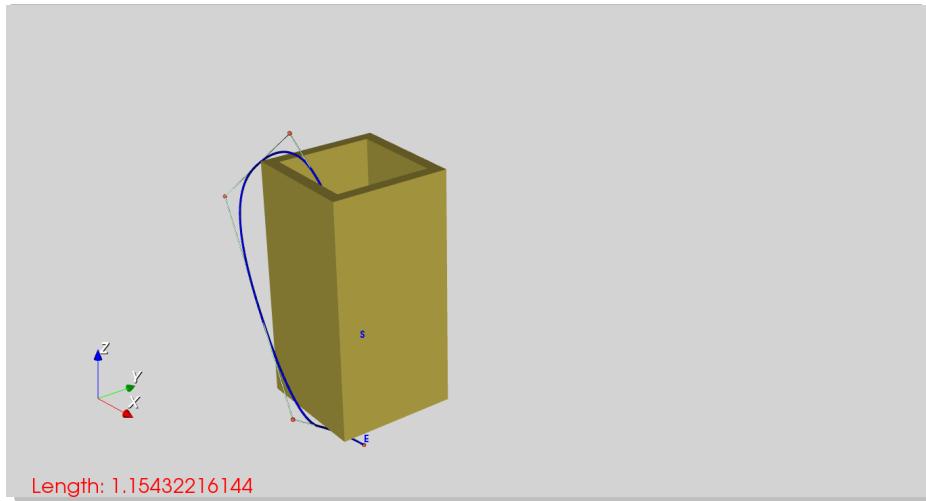


Figure 119.: Test 91; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 2; Meth. C; Part. U; Config. 1.

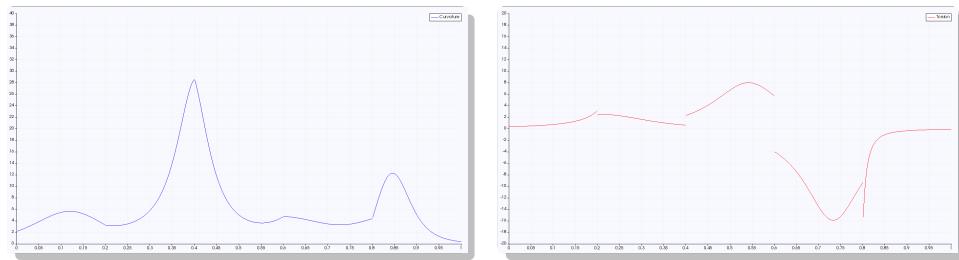
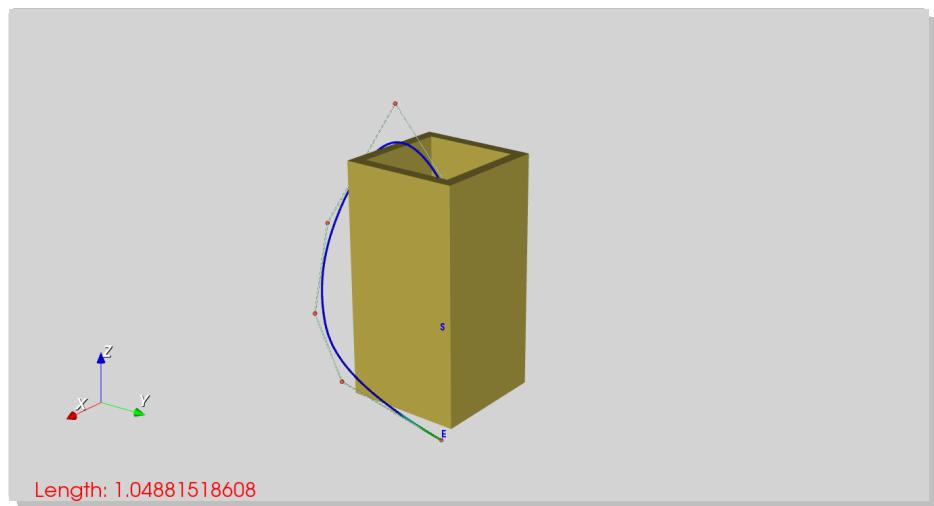
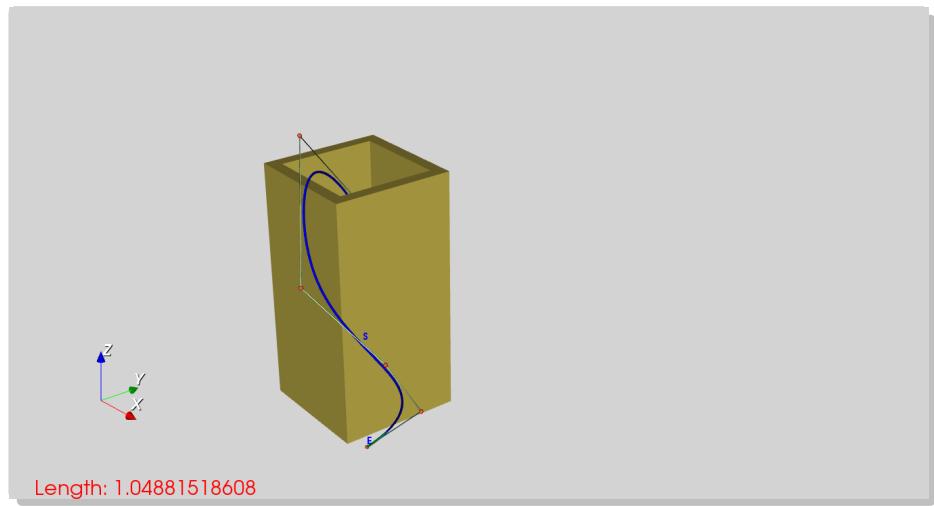


Figure 120.: Test 92; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 3; Meth. C; Part. U; Config. 1.

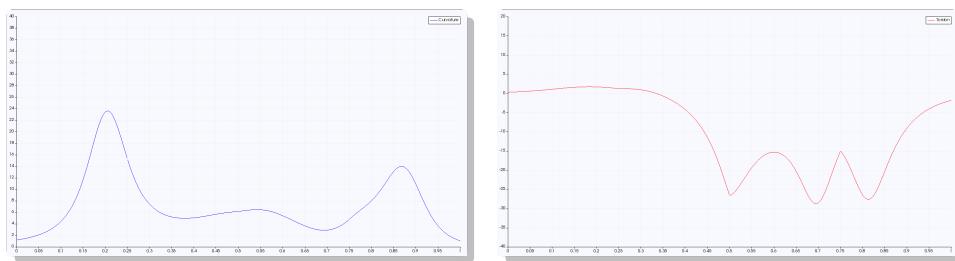
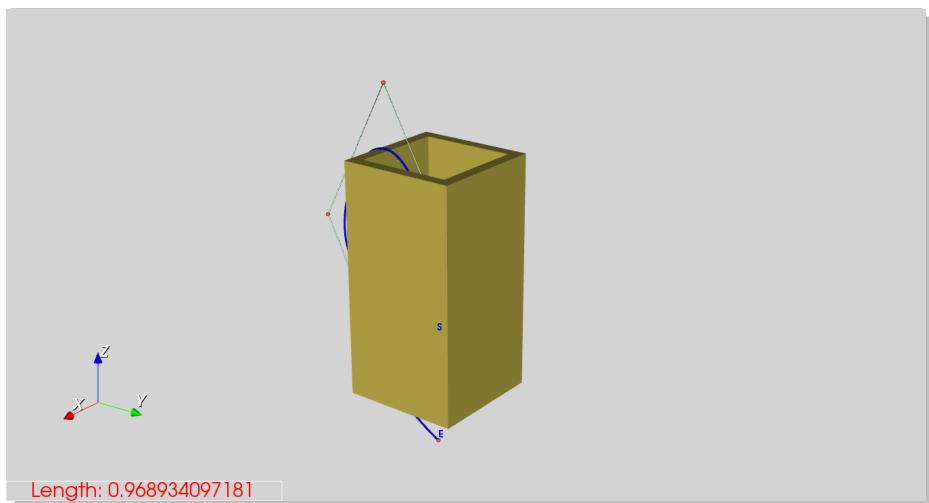
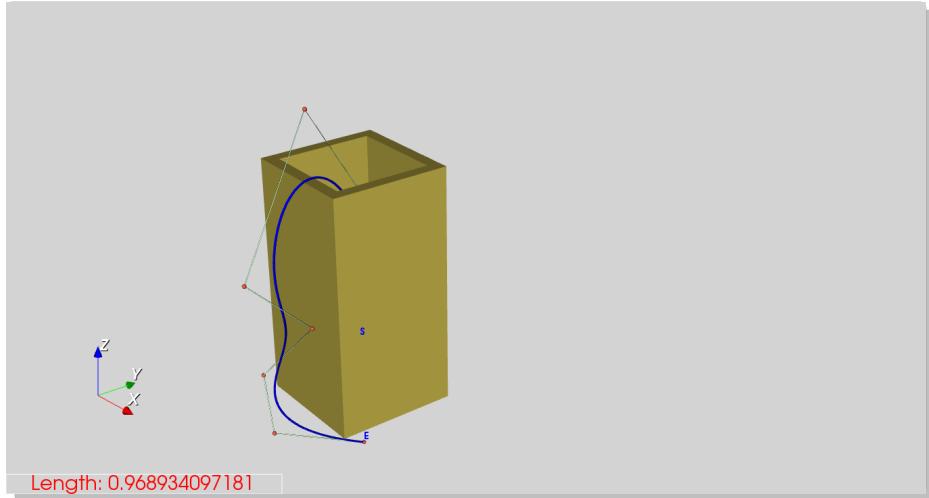


Figure 121.: Test 93; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 4; Meth. C; Part. U; Config. 1.

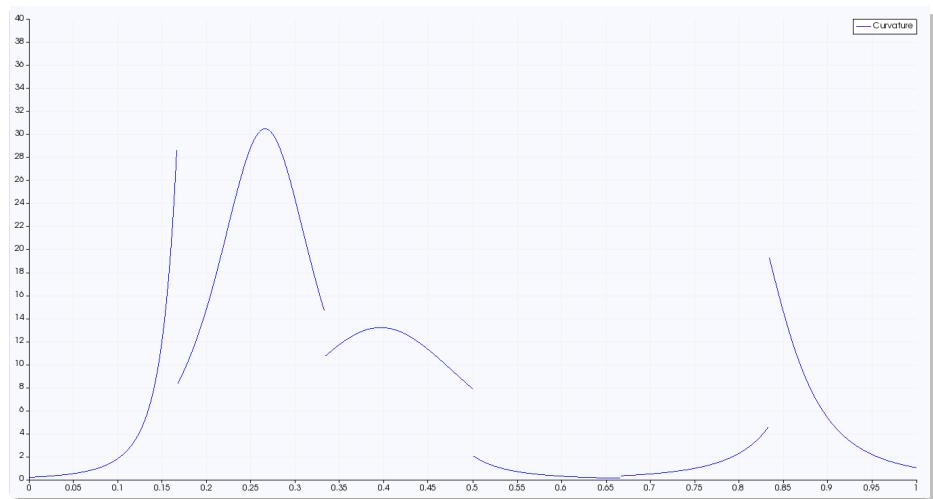
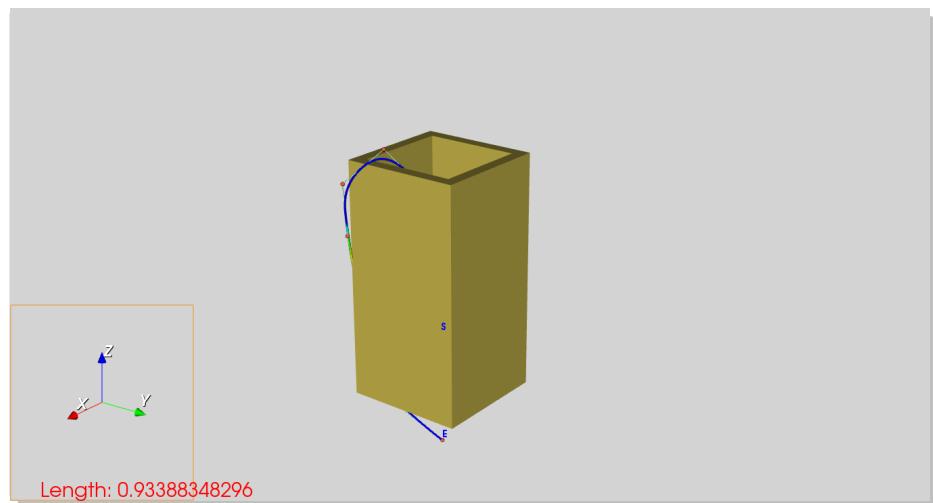
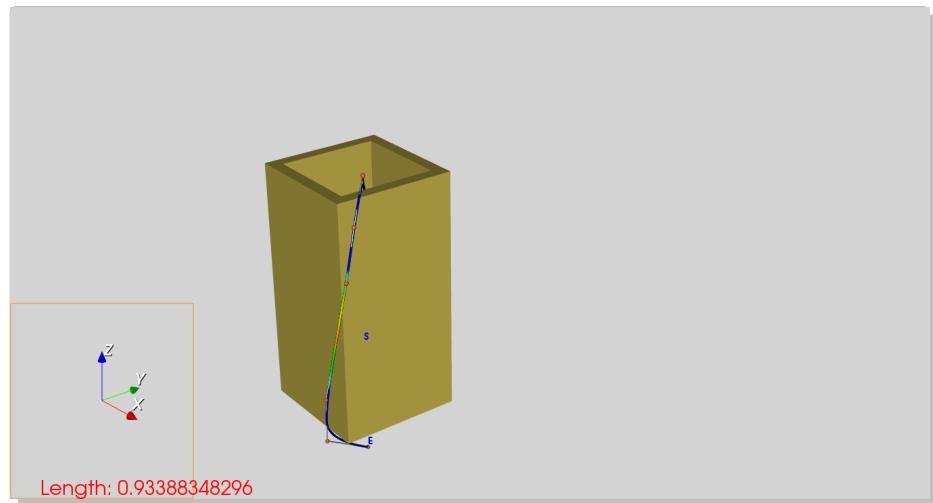


Figure 122.: Test 94; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 2; Meth. C; Part. U; Config. 2b.

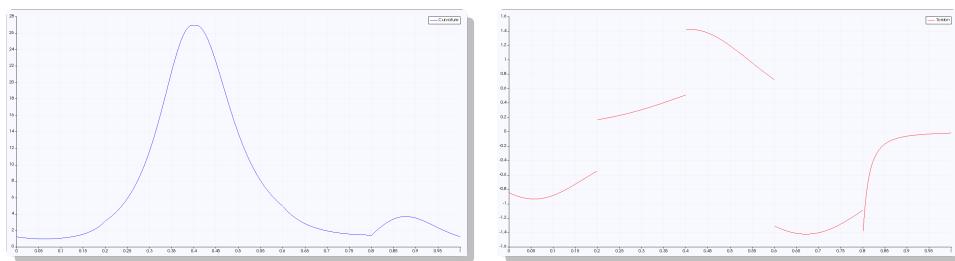
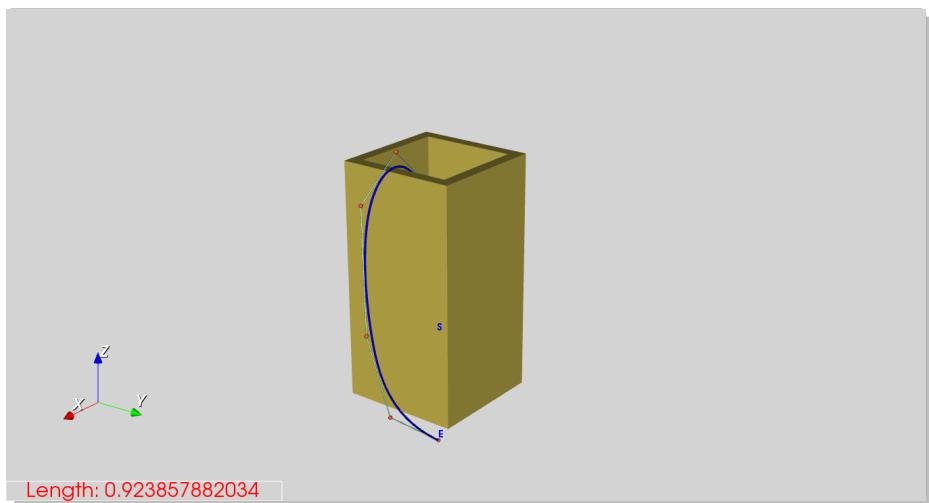
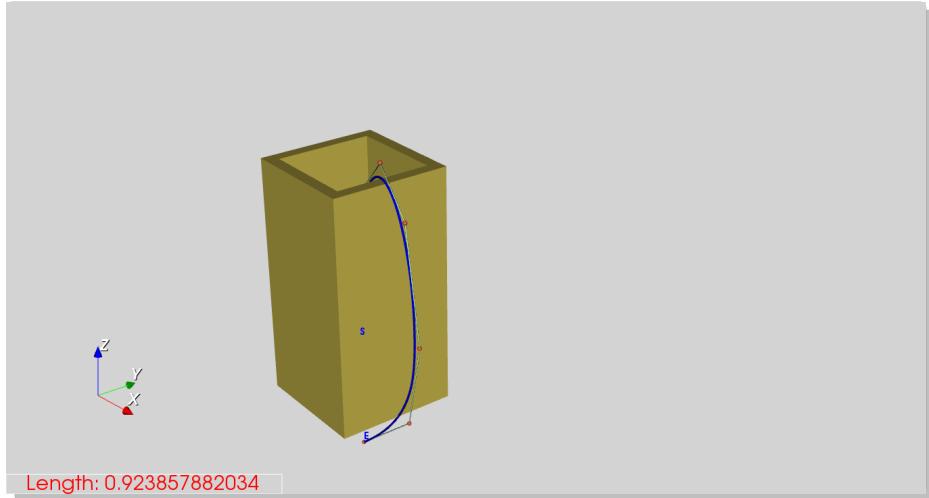


Figure 123.: Test 95; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 3; Meth. C; Part. U; Config. 2b.

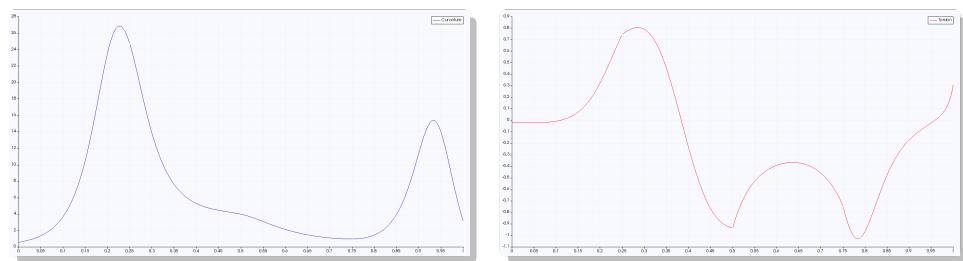
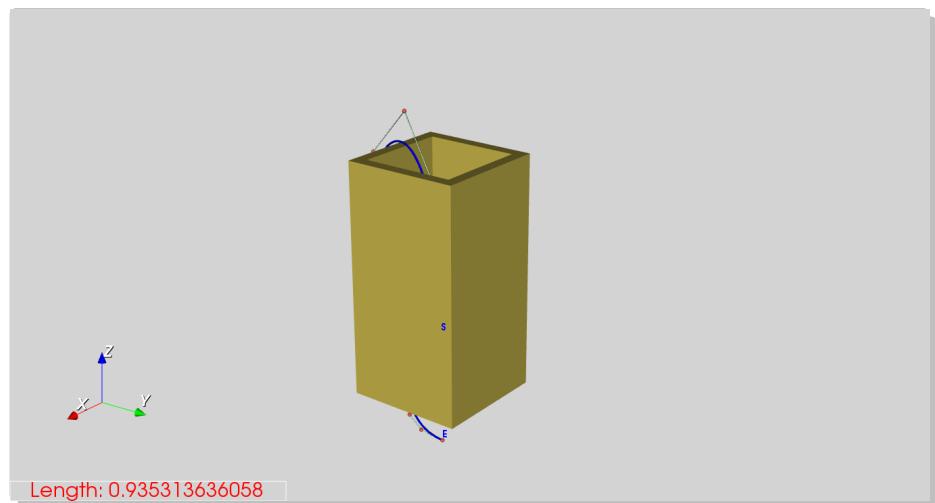
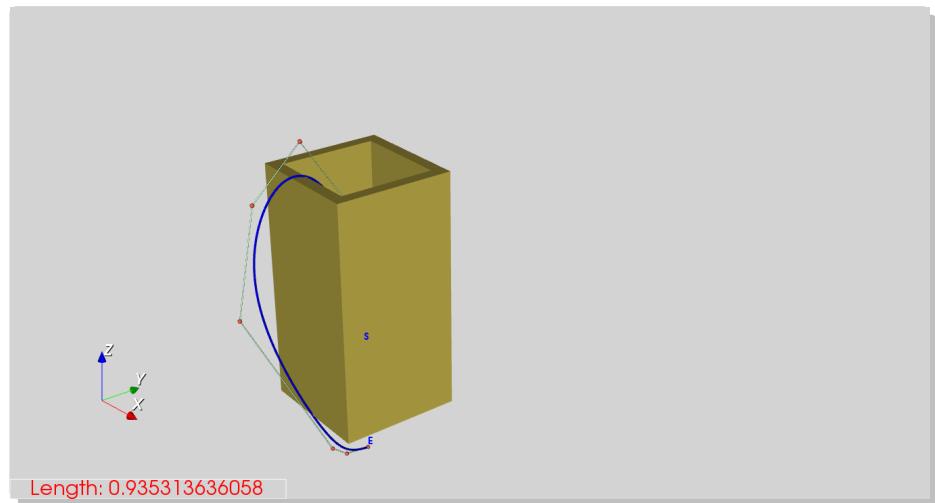


Figure 124.: Test 96; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 4; Meth. C; Part. U; Config. 2b.

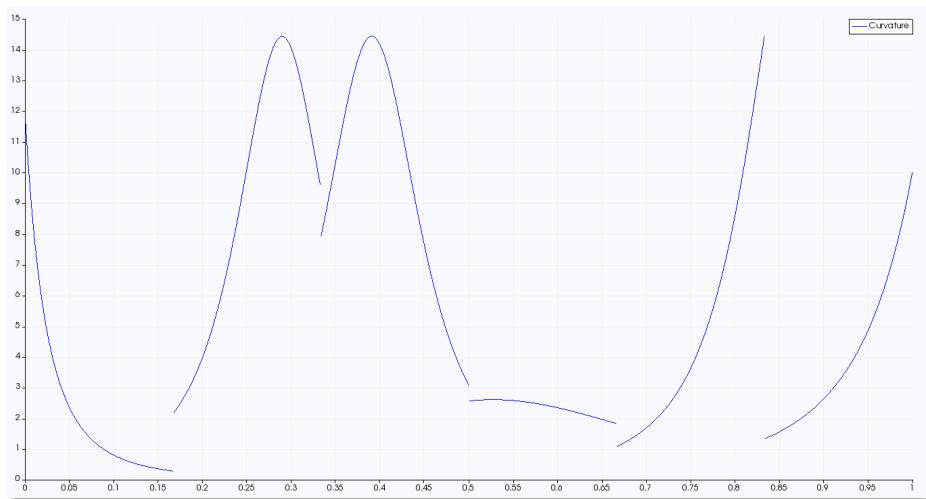
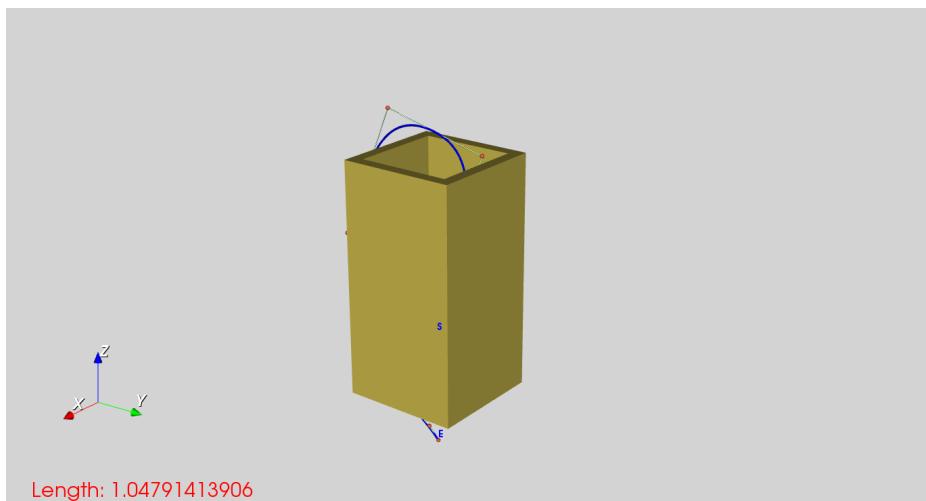
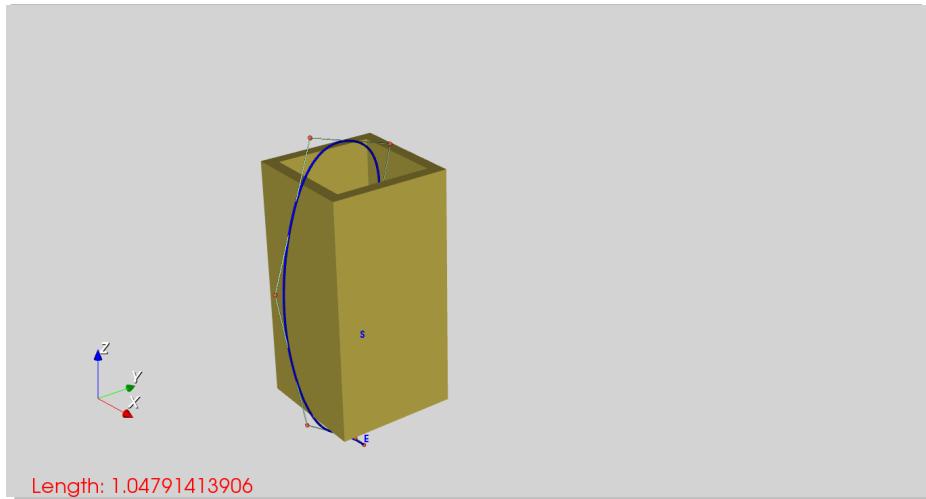


Figure 125.: Test 97; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 2; Meth. C; Part. U; Config. 3b.

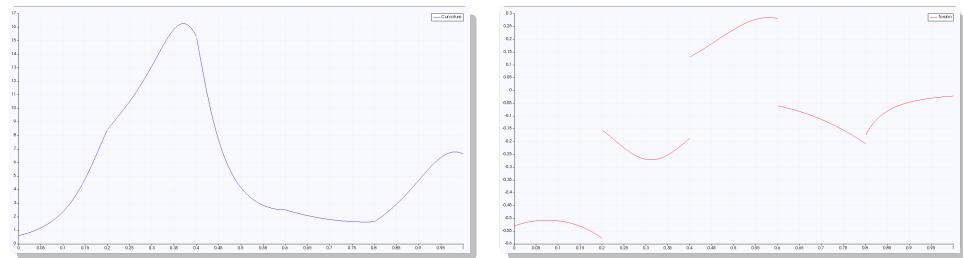
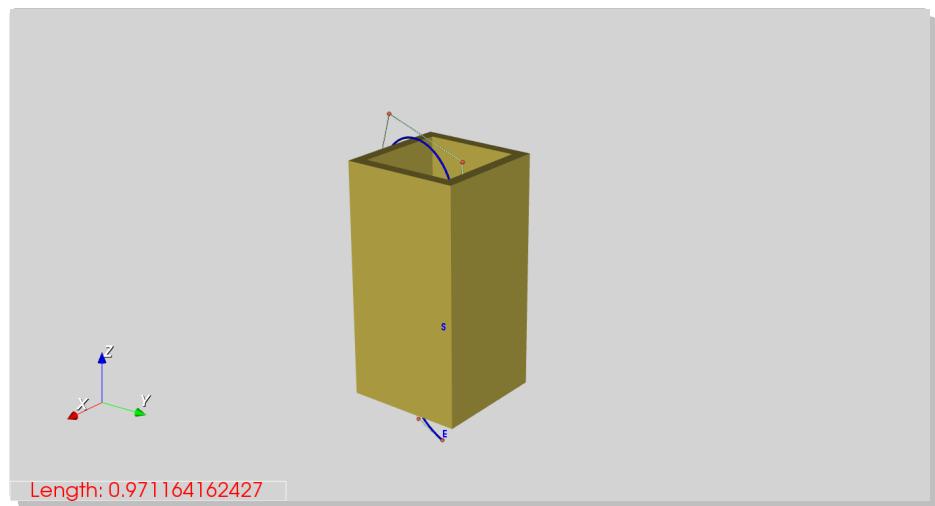
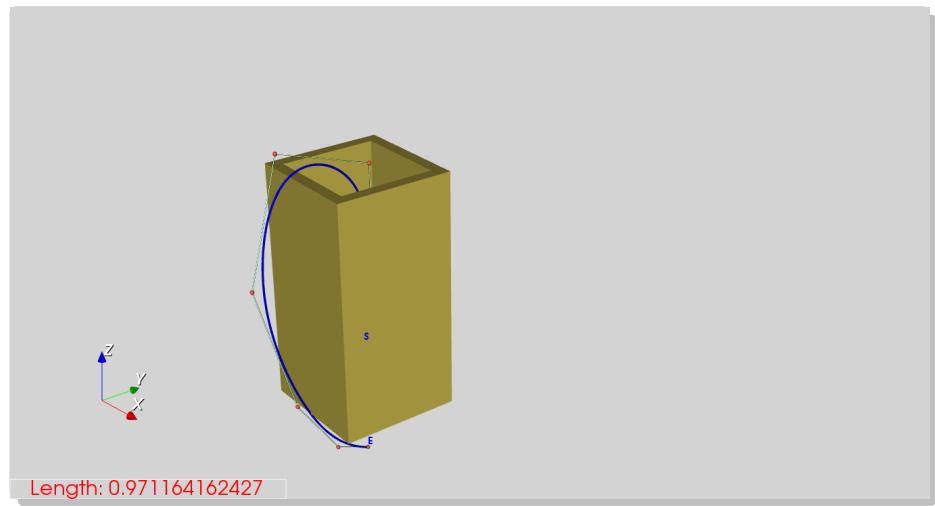


Figure 126.: Test 98; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 3; Meth. C; Part. U; Config. 3b.

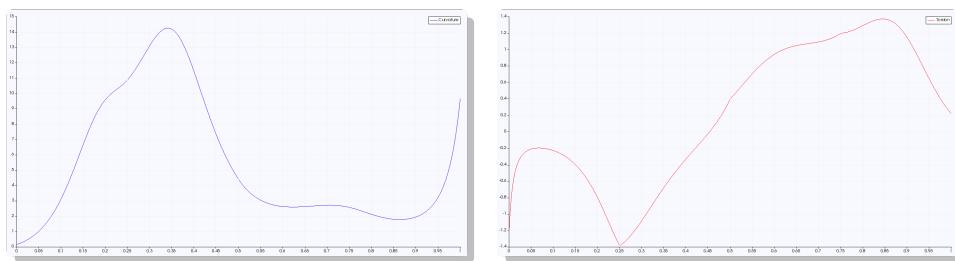
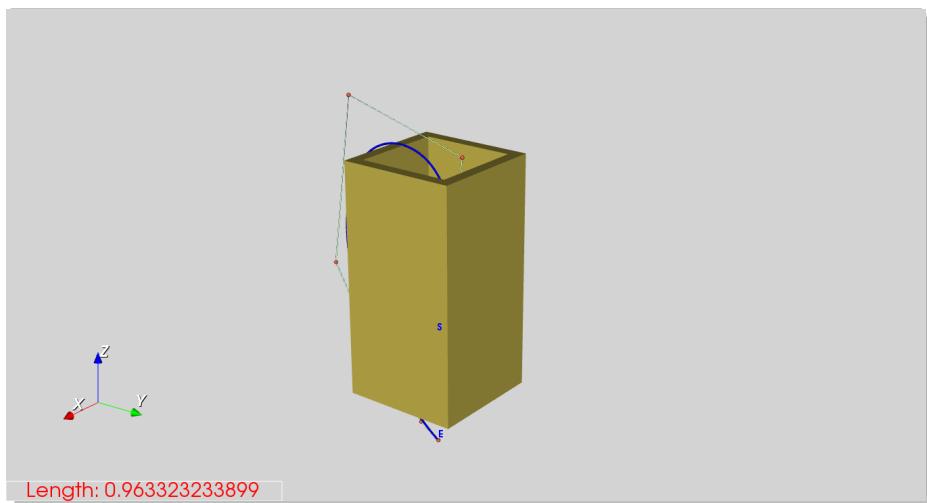
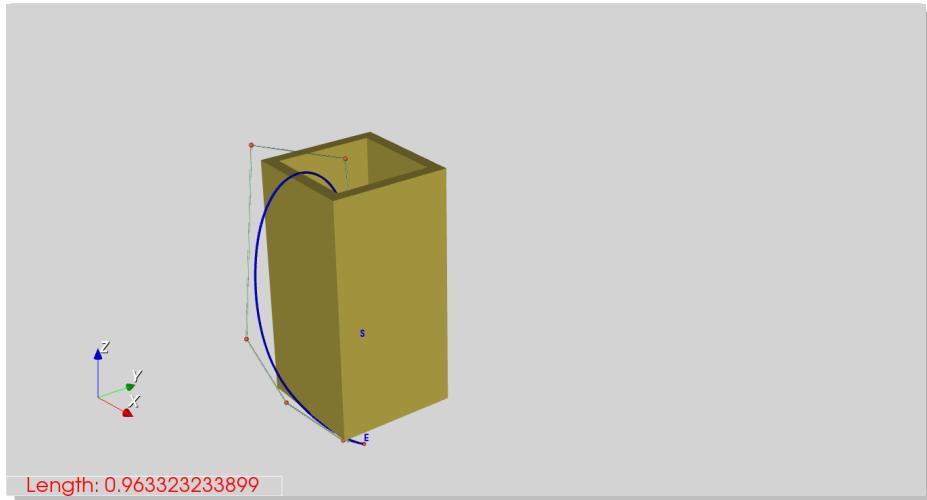


Figure 127.: Test 99; Scene 3;  $s \rightarrow e$   $[0.5, 0.5, 0.4] \rightarrow [0.5, 0.5, 0.2]$ ; Deg. 4; Meth. C; Part. U; Config. 3b.

# 8

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## CONCLUSIONS

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In this chapter we describe the evidence that emerges from the tests. Furthermore, we discuss possible future improvements of the project.

### 8.1 TESTS ANALYSIS

We present three scenes to do the tests. Scene 1 consists in 10 obstacles randomly disposed, scene 1b is the same scene with a more dense graph, scene 2 has 100 obstacles and scene 3 has only one bucket-shaped obstacle.

We set the starting and ending points to be at the extremes of the bounding box for scene 1 and scene 1b- i.e. the purpose of the tests in these scenes is to cross the area with the obstacles. For scene 2, we set the starting point in the centre of the crowded area and the aim is to manage to exit from the area. For scene 3, we set the starting point inside the bucket and we want to arrive under it.

Starting with the test for methods A and B, we manage to test all the possible configurations of scenes, degree, method, post-processing and knot partition. For method C, we tested 5 different parameter sets for the Simulated Annealing (SA).

Regarding the performances, the fastest method is B- to have an idea of the temporal scales, consider that, on a quad core Intel i5-2430M CPU at 2.40GHz with 8 Gb of RAM, an execution in scene 1 with post processing and adaptive knot partitions takes:

- 76 seconds for method A;
- 11 seconds for method B.

Method B is faster than method A, but we have to take into consideration that method B is more refined than method A because the latter needs to rebuild  $G_t$  when connecting the start and ending points.

It is difficult to compare method C to the previous two because of the different parameter sets, however, an execution of it in scene 1 with configuration 1 takes 168 seconds.

First of all, we notice that the application of the adaptive partition results in a deterioration of the curvature plots - i.e. an increase in magnitude of the curvature peaks - for the experiments with scenes 1, 1b and 2. However the experiments with scene 3 result in an improvement. Thus, this method is not always reliable in terms of the curve fairing.

The post-processing fulfills the purpose of simplifying the path. Consider, for instance, test 33 (Fig. 61) where the curvature plot has different peaks. After the application of post-processing, we obtain test 34 (Fig. 62) where the curvature peaks are mitigated.

The degree increase algorithm is improving the curvature: the plots are continuous for degree 3 and continuous and smooth for degree 4. Unfortunately, it is not reliable for the torsion (not shown in the tests) because, by adding aligned vertices, we force plane changes on zero-curvature points, where the torsion is not defined.

Method C produces high quality curves (see tests from 74 to 99) with low peaks of curvature and torsion. Moreover, this solution is not conditioned by the problem in degree increase mentioned before, the plots of the torsion are good.

An disadvantage of this solution is the discretization of collision check. Thus, depending on the parameters, it is possible that the path intersects an obstacle without noticing it. Other disadvantages are the slower execution time and the difficulty in finding the right values of the annealing parameters. In fact, wrong values of warming, or an insufficient number of trials can *freeze* the system in a not optimal status. Furthermore, it is necessary to adapt the parameters to different problems. For instance, the configuration 2 and 3 are not fitted for tests from 94 to 99: using those settings is not enough to let the system converge in an admissible state.

Regarding the complexity, we have that the highest cost which is  $\mathcal{O}(|O| \log |O|)$  in the number of obstacles  $|O|$ , comes from the creation of the scene. A run on the scene have complexity

- $\mathcal{O}(|O| \log |O|)$  for method A;
- $\mathcal{O}(|O| \log |O| + |P||O|)$  for method B, where  $|P|$  is the number of vertices in the control polygon;
- $\mathcal{O}(|O| \log |O| + \text{len}(P)|O|)$  for method C, where  $\text{len}(P)$  is the length of the control polygon.

## 8.2 FUTURE IMPROVEMENTS

Considering the different benefits and drawback of the implemented solutions, we advice to insist on a mixed approach to the problem, analytical and stochastic.

An new interesting solution might be implementing a stochastic optimization on the path obtained from solution 1 or solution 2, that is obstacle-free guaranteed. This hypothetical stochastic optimization must avoid states that violates the Convex Hull Property (CHP), and it can work directly on the state space without the Lagrangian relaxation. In fact, in that scenario the initial status is already obstacle-free. Furthermore, we believe that the optimization process do not need to explore too much the state space trespassing obstacle zones.

We believe that the described process can be very effective in improving curvature, torsion and length of the path. It can obtain curves with the quality of the implemented third solution and without the disadvantages of it: the slow computation and the possible collision errors caused by the discretization of the inclusion checks.

Another improvement could be studying different basic structures besides the graph extract from Voronoi Diagram (VD). For instance, Rapidly-expanding Random Tree (RRT).





Part IV  
APPENDIX



# A

---

## SOURCE CODE

---

### A.1 CLASSES

#### A.1.1 *voronizer.py*

```
 1 import numpy as np
 2 import numpy.linalg
 3 import scipy as sp
 4 import scipy.spatial
 5 import networkx as nx
 6 import numpy.linalg
 7 import polyhedron
 8 import polyhedronsContainer
 9 import path
10 import uuid
11 import xml.etree.cElementTree as ET
12
13 class Voronizer:
14     _pruningMargin = 0.3
15
16     def __init__(self, sites=np.array([]), bsplineDegree=4, adaptivePartition=False):
17         self._shortestPath = path.Path(bsplineDegree, adaptivePartition)
18         self._sites = sites
19         self._graph = nx.Graph()
20         self._tGraph = nx.DiGraph()
21         self._startTriplet = None
22         self._endTriplet = None
23         self._polyhedronsContainer = polyhedronsContainer.PolyhedronsContainer()
24         self._pathStart = np.array([])
25         self._pathEnd = np.array([])
26         self._startId = uuid.uuid4()
27         self._endId = uuid.uuid4()
28         self._bsplineDegree = bsplineDegree
29
30     def setBsplineDegree(self, bsplineDegree):
31         self._bsplineDegree = bsplineDegree
32         self._shortestPath.setBsplineDegree(bsplineDegree)
33
34     def setAdaptivePartition(self, adaptivePartition):
35         self._shortestPath.setAdaptivePartition(adaptivePartition)
36
37     def setCustomSites(self, sites):
38         self._sites = sites
39
40     def setRandomSites(self, number, seed=None):
41         if seed != None:
42             np.random.seed(0)
43         self._sites = sp.rand(number,3)
44
45     def addPolyhedron(self, polyhedron):
46         self._polyhedronsContainer.addPolyhedron(polyhedron)
47
48     def addBoundingBox(self, a, b, maxEmptyArea=1, invisible=True, verbose=False):
49         if verbose:
50             print('Add bounding box', flush=True)
51
52         self._polyhedronsContainer.addBoundingBox(a,b,maxEmptyArea, invisible)
```

```

53
54     def setPolyhedronsSites(self, verbose=False):
55         if verbose:
56             print('Set sites for Voronoi', flush=True)
57
58         sites = []
59         for polyhedron in self._polyhedronsContainer.polyhedrons:
60             sites.extend(polyhedron.allPoints)
61
62         self._sites = np.array(sites)
63
64     def makeVoroGraph(self, prune=True, verbose=False, debug=False):
65         if verbose:
66             print('Calculate Voronoi cells', flush=True)
67         ids = {}
68         vor = sp.spatial.Voronoi(self._sites)
69
70         if verbose:
71             print('Make pruned Graph from cell edges ', end='', flush=True)
72             printDotBunch = 0
73         vorVer = vor.vertices
74         for ridge in vor.ridge_vertices:
75             if verbose:
76                 if printDotBunch == 0:
77                     print('.', end='', flush=True)
78                 printDotBunch = (printDotBunch+1)%10
79
80             for i in range(1, len(ridge)):
81                 for j in range(i):
82                     if (ridge[i] != -1) and (ridge[j] != -1):
83                         a = vorVer[ridge[i]]
84                         b = vorVer[ridge[j]]
85                         if (not prune) or (not self._polyhedronsContainer.segmentIntersectPolyhedrons(a,b, intersectionMargin
86                                         ↪ = self._pruningMargin)):
87                             if tuple(a) in ids.keys():
88                                 idA = ids[tuple(a)]
89                             else:
90                                 idA = uuid.uuid4()
91                                 self._graph.add_node(idA, coord=a)
92                                 ids[tuple(a)] = idA
93
94                             if tuple(b) in ids.keys():
95                                 idB = ids[tuple(b)]
96                             else:
97                                 idB = uuid.uuid4()
98                                 self._graph.add_node(idB, coord=b)
99                                 ids[tuple(b)] = idB
100
101                         self._graph.add_edge(idA, idB, weight=np.linalg.norm(a-b))
102
103             if verbose:
104                 print('', flush=True)
105
106     self._createTripleGraph(verbose, debug)
107
108     def calculateShortestPath(self, start, end, attachMode='near', prune=True, useMethod='cleanPath', postSimplify=True,
109                               ↪ verbose=False, debug=False):
110         """
111         useMethod: cleanPath; trijkstra; annealing; annealingPro; none
112         """
113         if useMethod == 'trijkstra' or useMethod == 'cleanPath' or useMethod == 'annealing' or useMethod == 'annealingPro' or
114             ↪ useMethod == 'none':
115             if verbose:
116                 print('Attach start and end points', flush=True)
117             if attachMode=='near':
118                 self._attachToGraphNear(start, end, prune)
119             elif attachMode=='all':
120                 self._attachToGraphAll(start, end, prune)
121             else:
122                 self._attachToGraphNear(start, end, prune)
123
124             self._attachSpecialStartEndTriples(verbose)
125
126             self._pathStart = start
127             self._pathEnd = end
128
129             if useMethod == 'trijkstra':
130                 self._removeCollidingTriples(verbose, debug)
131
132             triPath = self._dijkstra(verbose, debug)
133             path = self._extractPath(triPath, verbose)
134             self._shortestPath.assignValues(path, self._polyhedronsContainer)

```

```

132
133     if useMethod == 'cleanPath' or useMethod == 'annealingPro':
134         self._shortestPath.clean(verbose, debug)
135     elif useMethod == 'annealing':
136         self._shortestPath.anneal(verbose)
137
138     #print(self._bsplineDegree)
139     if useMethod != 'annealing' and useMethod != 'none':
140         if self._bsplineDegree == 3:
141             self._shortestPath.addNAlignedVertxes(1, verbose, debug)
142         if self._bsplineDegree == 4:
143             self._shortestPath.addNAlignedVertxes(2, verbose, debug)
144
145     if useMethod == 'annealingPro':
146         self._shortestPath.annealPro(verbose)
147
148     if postSimplify:
149         self._shortestPath.simplify(verbose, debug)
150
151
152     def plotSites(self, plotter, verbose=False):
153         if verbose:
154             print('Plot Sites', end='', flush=True)
155
156         if self._sites.size > 0:
157             plotter.addPoints(self._sites, plotter.COLOR_SITES, thick=True)
158
159     def plotPolyhedrons(self, plotter, verbose=False):
160         if verbose:
161             print('Plot Polyhedrons', end='', flush=True)
162
163         for poly in self._polyhedronsContainer.polyhedrons:
164             poly.plot(plotter)
165             if verbose:
166                 print('.', end='', flush=True)
167
168         if verbose:
169             print('', flush=True)
170
171     def plotShortestPath(self, plotter, verbose=False):
172         if verbose:
173             print('Plot shortest path', flush=True)
174
175         if self._shortestPath.vertices.size > 0:
176             if self._polyhedronsContainer.hasBoundingBox:
177                 splineThickness = np.linalg.norm(np.array(self._polyhedronsContainer.boundingBoxB) - np.array(self._polyhedronsContainer.boundingBoxA)) / 1000.
178                 pointThickness = splineThickness * 2.
179                 lineThickness = splineThickness / 2.
180
181                 plotter.addPolyLine(self._shortestPath.vertices, plotter.COLOR_CONTROL_POLIG, thick=True, thickness=
182                                 ↪ lineThickness)
183                 plotter.addPoints(self._shortestPath.vertices, plotter.COLOR_CONTROL_POINTS, thick=True, thickness=
184                                 ↪ pointThickness)
185                 plotter.addBSpline(self._shortestPath, self._bsplineDegree, plotter.COLOR_PATH, thick=True, thickness=
186                                 ↪ splineThickness)
187
188             else:
189                 plotter.addPolyLine(self._shortestPath.vertices, plotter.COLOR_CONTROL_POLIG, thick=True)
190                 plotter.addPoints(self._shortestPath.vertices, plotter.COLOR_CONTROL_POINTS, thick=True)
191                 plotter.addBSpline(self._shortestPath, self._bsplineDegree, plotter.COLOR_PATH, thick=True)
192
193
194     def plotGraph(self, plotter, verbose=False):
195         if verbose:
196             print('Plot shortest path', flush=True)
197
198         plotter.addGraph(self._graph, plotter.COLOR_GRAPH)
199
200     def extractXmlTree(self, root):
201         if self._polyhedronsContainer.hasBoundingBox:
202             xmlBoundingBox = ET.SubElement(root, 'boundingBox')
203             ET.SubElement(xmlBoundingBox, 'a', x=str(self._polyhedronsContainer.boundingBoxA[0]), y=str(self._polyhedronsContainer.boundingBoxA[1]), z=str(self._polyhedronsContainer.boundingBoxA[2]))
204             ET.SubElement(xmlBoundingBox, 'b', x=str(self._polyhedronsContainer.boundingBoxB[0]), y=str(self._polyhedronsContainer.boundingBoxB[1]), z=str(self._polyhedronsContainer.boundingBoxB[2]))
205
206             xmlPolyhedrons = ET.SubElement(root, 'polyhedrons')
207             for polyhedron in self._polyhedronsContainer.polyhedrons:
208                 xmlPolyhedron = polyhedron.extractXmlTree(xmlPolyhedrons)
209
210
211     def importXmlTree(self, root, maxEmptyArea):
212         xmlBoundingBox = root.find('boundingBox')

```

```

208     if xmlBoundingBox:
209         xmlA = xmlBoundingBox.find('a')
210         xmlB = xmlBoundingBox.find('b')
211
212         self._polyhedronsContainer.hasBoundingBox = True
213         self._polyhedronsContainer.boundingBoxA = [float(xmlA.attrib['x']), float(xmlA.attrib['y']), float(xmlA.attrib['z'
214             ↪ ''])]
215         self._polyhedronsContainer.boundingBoxB = [float(xmlB.attrib['x']), float(xmlB.attrib['y']), float(xmlB.attrib['z'
216             ↪ ''])]
217
218     xmlPolyhedrons = root.find('polyhedrons')
219     if xmlPolyhedrons:
220         for xmlPolyhedron in xmlPolyhedrons.iter('polyhedron'):
221             invisible = False
222             if 'invisible' in xmlPolyhedron.attrib.keys():
223                 invisible = bool(eval(xmlPolyhedron.attrib['invisible']))
224
225             boundingBox = False
226             if 'boundingBox' in xmlPolyhedron.attrib.keys():
227                 boundingBox = bool(eval(xmlPolyhedron.attrib['boundingBox']))
228
229             faces = []
230             for xmlFace in xmlPolyhedron.iter('face'):
231                 vertexes = []
232                 for xmlVertex in xmlFace.iter('vertex'):
233                     vertexes.append([float(xmlVertex.attrib['x']), float(xmlVertex.attrib['y']), float(xmlVertex.attrib['
234                         ↪ z'])])
235
236             faces.append(vertexes)
237
238             newPolyhedron = polyhedron.Polyhedron(faces=np.array(faces), invisible=invisible, maxEmptyArea=maxEmptyArea,
239                 ↪ boundingBox=boundingBox)
240             self._polyhedronsContainer.addPolyhedron(newPolyhedron)
241
242     def _attachToGraphNear(self, start, end, prune):
243         firstS = True
244         firstE = True
245         minAttachS = None
246         minAttachE = None
247         minDistS = 0.
248         minDistE = 0.
249         for node, nodeAttr in self._graph.node.items():
250             if (not prune) or (not self._polyhedronsContainer.segmentIntersectPolyhedrons(start, nodeAttr['coord'],
251                 ↪ intersectionMargin= self._pruningMargin)):
252                 if firstS:
253                     minAttachS = node
254                     minDistS = np.linalg.norm(start - nodeAttr['coord'])
255                     firstS = False
256                 else:
257                     currDist = np.linalg.norm(start - nodeAttr['coord'])
258                     if currDist < minDistS:
259                         minAttachS = node
260                         minDistS = currDist
261
262             if (not prune) or (not self._polyhedronsContainer.segmentIntersectPolyhedrons(end, nodeAttr['coord'],
263                 ↪ intersectionMargin= self._pruningMargin)):
264                 if firstE:
265                     minAttachE = node
266                     minDistE = np.linalg.norm(end - nodeAttr['coord'])
267                     firstE = False
268                 else:
269                     currDist = np.linalg.norm(end - nodeAttr['coord'])
270                     if currDist < minDistE:
271                         minAttachE = node
272                         minDistE = currDist
273
274             if minAttachS != None:
275                 self._addNodeToTGraph(self._startId, start, minAttachS, minDistS, rightDirection=True)
276             if minAttachE != None:
277                 self._addNodeToTGraph(self._endId, end, minAttachE, minDistE, rightDirection=False)
278
279     def _attachToGraphAll(self, start, end, prune):
280         for node, nodeAttr in self._graph.node.items():
281             if (not prune) or (not self._polyhedronsContainer.segmentIntersectPolyhedrons(start, nodeAttr['coord'],
282                 ↪ intersectionMargin= self._pruningMargin)):
283                 self._addNodeToTGraph(self._startId, start, node, np.linalg.norm(start - nodeAttr['coord']), rightDirection=
284                     ↪ True)
285             if (not prune) or (not self._polyhedronsContainer.segmentIntersectPolyhedrons(end, nodeAttr['coord'],
286                 ↪ intersectionMargin= self._pruningMargin)):
287                 self._addNodeToTGraph(self._endId, end, node, np.linalg.norm(end - nodeAttr['coord']), rightDirection=False)
288
289     def _addNodeToTGraph(self, newId, coord, attachId, dist, rightDirection):

```

```

281     self._graph.add_node(newId, coord=coord)
282     self._graph.add_edge(newId, attachId, weight=dist)
283     for otherId in filter(lambda node: node != newId, self._graph.neighbors(attachId)):
284         newTriplet = uuid.uuid4()
285         if rightDirection:
286             self._tGraph.add_node(newTriplet, triplet=[newId,attachId,otherId])
287             self._tGraph.add_edges_from([(newTriplet, otherTriplet, {'weight':dist}) for otherTriplet in self._tGraph.
288                                         nodes() if self._tGraph.node[otherTriplet]['triplet'][0] == attachId and self._tGraph.node[
289                                         otherTriplet]['triplet'][1] == otherId])
290         else:
291             self._tGraph.add_node(newTriplet, triplet=[otherId,attachId,newId])
292             self._tGraph.add_edges_from([(otherTriplet, newTriplet, {'weight':dist}) for otherTriplet in self._tGraph.
293                                         nodes() if self._tGraph.node[otherTriplet]['triplet'][1] == otherId and self._tGraph.node[
294                                         otherTriplet]['triplet'][2] == attachId])
295
296     def _attachSpecialStartEndTriples(self, verbose):
297         #attach special starting and ending triplet
298         if verbose:
299             print('Create starting and ending triplets', flush=True)
300
301         self._startTriplet = uuid.uuid4()
302         self._endTriplet = uuid.uuid4()
303         self._tGraph.add_node(self._startTriplet, triplet = [self._startId,self._startId,self._startId], hit = False)
304         self._tGraph.add_node(self._endTriplet, triplet = [self._endId,self._endId,self._endId], hit = False)
305         self._tGraph.add_edges_from([(self._startTriplet, n, {'weight':0.}) for n in self._tGraph.nodes() if self._tGraph.
306                                     node[n]['triplet'][0] == self._startId])
307         self._tGraph.add_edges_from([(n, self._endTriplet, {'weight':0.}) for n in self._tGraph.nodes() if self._tGraph.node[
308                                     n]['triplet'][2] == self._endId])
309
310     def _createTripleGraph(self, verbose, debug):
311         #create triplets
312
313         if debug:
314             triplets_file = open("triplets.txt","w")
315
316         if verbose:
317             print('Create triplets ', end='', flush=True)
318             printDotBunch = 0
319
320         tripletIdList = {}
321         def getUniqueId(triplet):
322             if tuple(triplet) in tripletIdList.keys():
323                 tripletId = tripletIdList[tuple(triplet)]
324             else:
325                 tripletId = uuid.uuid4()
326                 tripletIdList[tuple(triplet)] = tripletId
327                 self._tGraph.add_node(tripletId, triplet = triplet)
328
329         return tripletId
330
331
332         for edge in self._graph.edges():
333             if verbose:
334                 if printDotBunch == 0:
335                     print('.', end='', flush=True)
336                 printDotBunch = (printDotBunch+1)%10
337
338             tripletsSxOutgoing = []
339             tripletsSxIngoing = []
340             tripletsDxOutgoing = []
341             tripletsDxIngoing = []
342
343             for nodeSx in filter(lambda node: node != edge[1], self._graph.neighbors(edge[0])):
344                 tripletId = getUniqueId([nodeSx,edge[0],edge[1]])
345                 tripletsSxOutgoing.append(tripletId)
346                 if debug:
347                     triplets_file.write('Sx0: {}\n'.format(self._tGraph.node[tripletId]['triplet']))
348
349                 tripletId = getUniqueId([edge[1],edge[0],nodeSx])
350                 tripletsSxIngoing.append(tripletId)
351                 if debug:
352                     triplets_file.write('SxI: {}\n'.format(self._tGraph.node[tripletId]['triplet']))
353
354             for nodeDx in filter(lambda node: node != edge[0], self._graph.neighbors(edge[1])):
355                 tripletId = getUniqueId([nodeDx,edge[1],edge[0]])
356                 tripletsDxOutgoing.append(tripletId)
357                 if debug:
358                     triplets_file.write('Dx0: {}\n'.format(self._tGraph.node[tripletId]['triplet']))
359
360                 tripletId = getUniqueId([edge[0],edge[1],nodeDx])
361                 tripletsDxIngoing.append(tripletId)
362                 if debug:
363
364

```

```

357         triplets_file.write('DxI: {}\\n'.format(self._tGraph.node[tripletId]['triplet']))
358
359     for tripletSx in tripletsSxOutgoing:
360         for tripletDx in tripletsDxIngoing:
361             self._tGraph.add_edge(tripletSx, tripletDx, {'weight':self._graph.edge[self._tGraph.node[tripletSx][
362                 '→ triplet'][0]][self._tGraph.node[tripletDx][0]]['weight']} )
363
364     for tripletDx in tripletsDxOutgoing:
365         for tripletSx in tripletsSxIngoing:
366             self._tGraph.add_edge(tripletDx, tripletSx, {'weight':self._graph.edge[self._tGraph.node[tripletDx][
367                 '→ triplet'][0]][self._tGraph.node[tripletSx][0]]['weight']} )
368
369     if verbose:
370         print('', flush=True)
371
372     if debug:
373         triplets_file.close()
374
375 def _dijkstra(self, verbose, debug):
376     try:
377         if verbose:
378             print('Dijkstra algorithm', flush=True)
379
380         length, triPath=nx.bidirectional_dijkstra(self._tGraph, self._startTriplet, self._endTriplet)
381
382     except (nx.NetworkXNoPath, nx.NetworkXError):
383         print('ERROR: Impossible to find a path')
384         triPath = []
385
386     return triPath
387
388 def _extractPath(self, triPath, verbose):
389     if verbose:
390         print('Extract path', flush=True)
391
392     path = []
393     for t in triPath:
394         path.append(self._graph.node[self._tGraph.node[t]['triplet'][1]]['coord'])
395
396     return np.array(path)
397
398 def _removeCollidingTriples(self, verbose, debug):
399     if verbose:
400         print('Remove colliding triples', flush=True)
401         printDotBunch = 0
402
403     toRemove = []
404     for triple in self._tGraph:
405         if verbose:
406             if printDotBunch == 0:
407                 print('.', end='', flush=True)
408             printDotBunch = (printDotBunch+1)%10
409
410             a = self._graph.node[self._tGraph.node[triple]['triplet'][0]]['coord']
411             b = self._graph.node[self._tGraph.node[triple]['triplet'][1]]['coord']
412             c = self._graph.node[self._tGraph.node[triple]['triplet'][2]]['coord']
413             intersect,intersectRes = self._polyhedronsContainer.triangleIntersectPolyhedrons(a, b, c)
414
415             if intersect:
416                 toRemove.append(triple)
417
418         if verbose:
419             print("", flush=True)
420
421     for triple in toRemove:
422         self._tGraph.remove_node(triple)

```

### A.1.2 *path.py*

```

1 import random
2 import math
3 import numpy as np
4 import scipy as sp
5 import scipy.interpolate
6

```

```

7 | class Path:
8 |     _initialTemperature = 10#1000
9 |     _trials = 100#100
10 |    _warmingRatio = 0.7#0.9
11 |    _minTemperature=0.001#0.0000001
12 |    _minDeltaEnergy=0.1
13 |    _maxVlambdaPert = 1000.
14 |    _maxVertexPertFactor = 100.
15 |    _initialVlambda = 0.
16 |    _changeVlambdaProbability = 0.05
17 |    _useArcLen = False
18 |    _ratioCurvTorsLen = [0.1, 0.1, 0.8]
19 |
20 |    def __init__(self, bsplineDegree, adaptivePartition):
21 |        self._bsplineDegree = bsplineDegree
22 |        self._adaptivePartition = adaptivePartition
23 |        self._vertexes = np.array([])
24 |        self._dimC = 0
25 |        self._polyhedronsContainer = []
26 |        self._vlambda = self._initialVlambda
27 |
28 |
29 |    @property
30 |    def vertexes(self):
31 |        return self._vertexes
32 |
33 |    def assignValues(self, path, polyhedronsContainer):
34 |        self._vertexes = path
35 |        self._dimC = self._vertexes.shape[1]
36 |
37 |        self._polyhedronsContainer = polyhedronsContainer
38 |        tau, u, spline, splineD1, splineD2, splineD3, curv, tors, arcLength, polLength = self._splinePoints(self._vertexes)
39 |        self._maxVertexPert = polLength / self._maxVertexPertFactor
40 |
41 |    def setBsplineDegree(self, bsplineDegree):
42 |        self._bsplineDegree = bsplineDegree
43 |
44 |    def setAdaptivePartition(self, adaptivePartition):
45 |        self._adaptivePartition = adaptivePartition
46 |
47 |    def clean(self, verbose, debug):
48 |        if verbose:
49 |            print('Clean path (avoid obstacles)', flush=True)
50 |
51 |        newPath = []
52 |        if len(self._vertexes) > 0:
53 |            a = self._vertexes[0]
54 |            newPath.append(self._vertexes[0])
55 |
56 |            for i in range(1, len(self._vertexes)-1):
57 |                v = self._vertexes[i]
58 |                b = self._vertexes[i+1]
59 |
60 |                intersect,intersectRes = self._polyhedronsContainer.triangleIntersectPolyhedrons(a, v, b)
61 |                if intersect:
62 |                    alpha = intersectRes[1]
63 |
64 |                    a1 = (1.-alpha)*a + alpha*v
65 |                    b1 = alpha*v + (1.-alpha)*b
66 |
67 |                    newPath.append(a1)
68 |                    newPath.append(v)
69 |                    newPath.append(b1)
70 |
71 |                    a = b1
72 |                else:
73 |                    newPath.append(v)
74 |
75 |                    a = v
76 |
77 |        if len(self._vertexes) > 0:
78 |            newPath.append(self._vertexes[len(self._vertexes)-1])
79 |
80 |        self._vertexes = np.array(newPath)
81 |
82 |
83 |    def anneal(self, verbose):
84 |        if verbose:
85 |            print('Anneal path', flush=True)
86 |
87 |

```

```

88     tau, u, self._spline, splineD1, splineD2, splineD3, curv, tors, arcLength, polLength = self._splinePoints(self.
89         ↪ _vertexes)
90     self._currentEnergy, self._maxCurvatureLength, self._currentConstraints = self._initializePathEnergy(self._vertexes,
91         ↪ self._spline, splineD1, splineD2, self._vlambda)
92
93     temperature = self._initialTemperature
94     while True:
95         initialEnergy = self._currentEnergy
96         numMovedLambda = 0
97         numMovedVertex = 0
98         for i in range(self._trials):
99             movedLambda,movedVertex = self._tryMove(temperature)
100            if movedLambda:
101                numMovedLambda += 1
102            if movedVertex:
103                numMovedVertex += 1
104            deltaEnergy = abs(initialEnergy - self._currentEnergy)
105            temperature = temperature * self._warmingRatio
106            if verbose:
107                print("T:{}; E:{}; DE:{}; L:{}; C:{}; ML:{}; MV:{}".format(temperature, self._currentEnergy, deltaEnergy,
108                    ↪ self._vlambda, self._currentConstraints, numMovedLambda, numMovedVertex), flush=True)
109
110        if (temperature < self._minTemperature) or (numMovedVertex > 0 and (deltaEnergy < self._minDeltaEnergy) and self.
111            ↪ _currentConstraints == 0.):
112            break
113
114    def annealPro(self, verbose):
115        if verbose:
116            print('Anneal path', flush=True)
117
118        tau, u, self._spline, splineD1, splineD2, splineD3, curv, tors, arcLength, polLength = self._splinePoints(self.
119            ↪ _vertexes)
120        self._currentEnergy = self._initializePathEnergyPro(self._vertexes, self._spline, splineD1, splineD2)
121
122        temperature = self._initialTemperature
123        while True:
124            initialEnergy = self._currentEnergy
125            numMovedVertex = 0
126            for i in range(self._trials):
127                movedVertex = self._tryMovePro(temperature)
128                if movedVertex:
129                    numMovedVertex += 1
130                deltaEnergy = abs(initialEnergy - self._currentEnergy)
131                temperature = temperature * self._warmingRatio
132                if verbose:
133                    print("T:{}; E:{}; DE:{}; MV:{}".format(temperature, self._currentEnergy, deltaEnergy, numMovedVertex), flush
134                        ↪ =True)
135
136        if (temperature < self._minTemperature) or (numMovedVertex > 0 and (deltaEnergy < self._minDeltaEnergy)):
137            break
138
139    def simplify(self, verbose, debug):
140        if verbose:
141            print('Simplify path (remove useless triples)', flush=True)
142        if self._bsplineDegree == 2:
143            self._simplify2()
144        elif self._bsplineDegree == 3:
145            self._simplify3()
146        elif self._bsplineDegree == 4:
147            self._simplify4()
148
149        def _simplify2(self):
150            simplifiedPath = []
151            if len(self._vertexes) > 0:
152                a = self._vertexes[0]
153                simplifiedPath.append(self._vertexes[0])
154                first = True
155                for i in range(1,len(self._vertexes)-1):
156                    v = self._vertexes[i]
157                    b = self._vertexes[i+1]
158                    keepV = False
159
160                    intersectCurr,nihil = self._polyhedronsContainer.triangleIntersectPolyhedrons(a, v, b)
161
162                    if not intersectCurr:
163                        if first:
164                            intersectPrec = False
165                        else:
166                            #a1 = self._vertexes[i-2]
167                            intersectPrec,nihil = self._polyhedronsContainer.triangleIntersectPolyhedrons(a1, a, b)

```

```

164     if i == len(self._vertexes)-2:
165         intersectSucc = False
166     else:
167         b1 = self._vertexes[i+2]
168         intersectSucc,nihil = self._polyhedronsContainer.triangleIntersectPolyhedrons(a, b, b1)
169
170     if intersectPrec or intersectSucc:
171         keepV = True
172
173     else:
174         keepV = True
175
176     if keepV:
177         first = False
178         simplifiedPath.append(v)
179         a1 = a
180         a = v
181
182     if len(self._vertexes) > 0:
183         simplifiedPath.append(self._vertexes[len(self._vertexes)-1])
184
185     self._vertexes = np.array(simplifiedPath)
186
187 def _simplify3(self):
188     simp = list(self._vertexes)
189     toEval = 0
190     while toEval < len(simp)-2:
191         toEval += 1
192         if toEval >= 3:
193             if toEval < len(simp)-1:
194                 if self._polyhedronsContainer.convexHullIntersectsPolyhedrons([simp[toEval-3], simp[toEval-2], simp[
195                     ↪ toEval-1], simp[toEval+1]]):
196                     continue
197
198             if toEval >= 2:
199                 if toEval < len(simp)-2:
200                     if self._polyhedronsContainer.convexHullIntersectsPolyhedrons([simp[toEval-2], simp[toEval-1], simp[
201                         ↪ toEval+1], simp[toEval+2]]):
202                         continue
203
204             if toEval < len(simp)-3:
205                 if self._polyhedronsContainer.convexHullIntersectsPolyhedrons([simp[toEval-1], simp[toEval+1], simp[toEval[
206                     ↪ +2], simp[toEval+3]]]):
207                     continue
208
209         del simp[toEval]
210         toEval -= 1
211
212     self._vertexes = np.array(simp)
213
214 def _simplify4(self):
215     simp = list(self._vertexes)
216     toEval = 0
217     while toEval < len(simp)-2:
218         toEval += 1
219         if toEval >= 4:
220             if toEval < len(simp)-1:
221                 if self._polyhedronsContainer.convexHullIntersectsPolyhedrons([simp[toEval-4], simp[toEval-3], simp[
222                     ↪ toEval-2], simp[toEval-1], simp[toEval+1]]):
223                     continue
224
225             if toEval >= 3:
226                 if toEval < len(simp)-2:
227                     if self._polyhedronsContainer.convexHullIntersectsPolyhedrons([simp[toEval-3], simp[toEval-2], simp[
228                         ↪ toEval-1], simp[toEval+1], simp[toEval+2]]):
229                     continue
230
231             if toEval >= 2:
232                 if toEval < len(simp)-3:
233                     if self._polyhedronsContainer.convexHullIntersectsPolyhedrons([simp[toEval-2], simp[toEval-1], simp[
234                         ↪ toEval+1], simp[toEval+2], simp[toEval+3]]):
235                     continue
236
237             if toEval < len(simp)-4:
238                 if self._polyhedronsContainer.convexHullIntersectsPolyhedrons([simp[toEval-1], simp[toEval+1], simp[toEval[
239                     ↪ +2], simp[toEval+3], simp[toEval+4]]]):
240                     continue
241
242         del(simp[toEval])
243         toEval -= 1
244
245     self._vertexes = np.array(simp)
246
247

```

```

239
240     def addNALignedVertexes(self, numVertexes, verbose, debug):
241         if verbose:
242             print('Increase degree', flush=True)
243
244         newPath = []
245         for i in range(1, len(self._vertexes)):
246             a = self._vertexes[i-1]
247             b = self._vertexes[i]
248             newPath.append(a)
249
250             if numVertexes == 1:
251                 n = 0.5 * a + 0.5 * b
252                 newPath.append(n)
253
254             elif numVertexes == 2:
255                 n1 = 0.33 * b + 0.67 * a
256                 n2 = 0.33 * a + 0.67 * b
257                 newPath.append(n1)
258                 newPath.append(n2)
259
260             if len(self._vertexes) > 0:
261                 newPath.append(self._vertexes[len(self._vertexes)-1])
262
263         self._vertexes = np.array(newPath)
264
265     def splinePoints(self):
266         return self._splinePoints(self._vertexes)
267
268     def _splinePoints(self, vertexes):
269
270         x = vertexes[:,0]
271         y = vertexes[:,1]
272         z = vertexes[:,2]
273
274         polLen = self._calculatePolyLength(vertexes)
275
276         tau,t = self._createKnotPartition(vertexes)
277
278         #[knots, coeff, degree]
279         tck = [t,[x,y,z], self._bsplineDegree]
280
281         u=np.linspace(0,1,(max(polLen*5,1000)),endpoint=True)
282
283         out = sp.interpolate.splev(u, tck)
284         outD1 = sp.interpolate.splev(u, tck, 1)
285         outD2 = sp.interpolate.splev(u, tck, 2)
286
287         spline = np.stack(out).T
288         splineD1 = np.stack(outD1).T
289         splineD2 = np.stack(outD2).T
290
291         if self._bsplineDegree >= 3:
292             outD3 = sp.interpolate.splev(u, tck, 3)
293             splineD3 = np.stack(outD3).T
294         else:
295             splineD3 = None
296
297         curv = []
298         tors = []
299         arcLength = 0.
300         for i in range(len(u)):
301             d1Xd2 = np.cross(splineD1[i], splineD2[i])
302             Nd1Xd2 = np.linalg.norm(d1Xd2)
303             Nd1 = np.linalg.norm(splineD1[i])
304
305             currCurv = 0.
306             if Nd1 >0.: #>= 1.:
307                 currCurv = Nd1Xd2 / math.pow(Nd1,3)
308
309             currTors = 0.
310             if self._bsplineDegree >= 3 and Nd1Xd2 > 0.: #>= 1.:
311                 try:
312                     currTors = np.dot(d1Xd2, splineD3[i]) / math.pow(Nd1Xd2, 2)
313                 except RuntimeWarning:
314                     currTors = 0.
315
316             curv.append(currCurv)
317             tors.append(currTors)
318
319             if i >= 1:
320                 dMin = min(prevNd1, Nd1)

```

```

321         dMax = max(prevNd1, Nd1)
322         arcLength += (u[i]-u[i-1]) * (dMin + ((dMax-dMin) / 2.))
323
324     prevNd1 = Nd1
325
326     return (tau, u, spline, splineD1, splineD2, splineD3, curv, tors, arcLength, polLength)
327
328     def _createKnotPartition(self, controlPolygon):
329         nv = len(controlPolygon)
330         nn = nv - self._bsplineDegree + 1
331
332         if not self._adaptivePartition:
333             T = np.linspace(0,1,nv-self._bsplineDegree+1,endpoint=True)
334         else:
335             d = [0]
336             for j in range(1, nv):
337                 d.append(d[j-1] + np.linalg.norm(controlPolygon[j] - controlPolygon[j-1]))
338             t = []
339             for i in range(nn-1):
340                 a = i * (nv-1) / (nn-1)
341                 ai = math.floor(a)
342                 ad = a - ai
343                 p = ad * controlPolygon[ai+1] + (1-ad) * controlPolygon[ai]
344                 l = d[ai] + np.linalg.norm(p - controlPolygon[ai])
345                 t.append(l / d[nv-1])
346
347             t.append(1.)
348
349             T = np.array(t)
350
351             Text = np.append([0]*self._bsplineDegree, T)
352             Text = np.append(Text, [1]*self._bsplineDegree)
353
354         return (T,Text)
355
356     def _initializePathEnergy(self, vertexes, spline, splineD1, splineD2, vlambda):
357         tau, u, spline, splineD1, splineD2, splineD3, curv, tors, arcLength, polLength = self._splinePoints(vertexes)
358         if self._useArcLen:
359             length = arcLength
360         else:
361             length = polLength
362
363         self._initialLength = length
364         maxCurvatureLength = self._calculateMaxCurvatureLength(length, curv, tors)
365         constraints = self._calculateConstraints(spline)
366         energy = maxCurvatureLength + vlambda * constraints
367
368         return (energy, maxCurvatureLength, constraints)
369
370     def _initializePathEnergyPro(self, vertexes, spline, splineD1, splineD2):
371         tau, u, spline, splineD1, splineD2, splineD3, curv, tors, arcLength, polLength = self._splinePoints(vertexes)
372         if self._useArcLen:
373             length = arcLength
374         else:
375             length = polLength
376
377         self._initialLength = length
378         energy = self._calculateMaxCurvatureLength(length, curv, tors)
379
380         return (energy)
381
382     def _tryMove(self, temperature):
383         """
384             Move the path or lambda multipliers in a neighbouring state,
385             with a certain acceptance probability.
386             Pick a random vertex (except extremes), and move
387             it in a random direction (with a maximum perturbation).
388             Use a lagrangian relaxation because we need to evaluate
389             min(measure(path)) given the constraint that all quadrilaterals
390             formed by 4 consecutive points in the path must be collision
391             free; where measure(path) is, depending of the choose method,
392             the length of the path or the mean
393             of the supplementary angles of each pair of edges of the path.
394             If neighbourMode=0 then move the node uniformly, if
395             neighbourMode=1 then move the node with gaussian probabilities
396             with mean in the perpendicular direction respect to the
397             previous-next nodes axis.
398
399         movedLambda = False
400         movedVertex = False
401         moveVlambda = random.random() < self._changeVlambdaProbability

```

```

403     if moveVlambda:
404         newVlambda = self._vlambda
405         newVlambda = newVlambda + (random.uniform(-1.,1.) * self._maxVlambdaPert)
406
407         newEnergy = self._calculatePathEnergyLambda(newVlambda)
408
409         #attention, different formula from below
410         if (newEnergy > self._currentEnergy) or (math.exp(-(self._currentEnergy-newEnergy)/temperature) >= random.random
411             ↪ ()):
412             self._vlambda = newVlambda
413             self._currentEnergy = newEnergy
414             movedLambda = True
415
416     else:
417         newVertexes = np.copy(self._vertexes)
418         movedV = random.randint(1,len(self._vertexes) - 2) #don't change extremes
419
420         moveC = random.randint(0,self._dimC - 1)
421         newVertexes[movedV][moveC] = newVertexes[movedV][moveC] + (random.uniform(-1.,1.) * self._maxVertexPert)
422
423         newEnergy,newMaxCurvatureLength,newConstraints = self._calculatePathEnergyVertex(newVertexes)
424
425         #attention, different formula from above
426         if (newEnergy < self._currentEnergy) or (math.exp(-(newEnergy-self._currentEnergy)/temperature) >= random.random
427             ↪ ()):
428             self._vertexes = newVertexes
429             self._currentEnergy = newEnergy
430             self._currentMaxCurvatureLength = newMaxCurvatureLength
431             self._currentConstraints = newConstraints
432             movedVertex = True
433
434     return (movedLambda, movedVertex)
435
436 def _tryMovePro(self, temperature):
437     movedVertex = False
438
439     newVertexes = np.copy(self._vertexes)
440     movedV = random.randint(1,len(self._vertexes) - 2) #don't change extremes
441
442     moveC = random.randint(0,self._dimC - 1)
443     newVertexes[movedV][moveC] = newVertexes[movedV][moveC] + (random.uniform(-1.,1.) * self._maxVertexPert)
444
445     if self._newPathFree(newVertexes):
446         newEnergy = self._calculatePathEnergyVertexPro(newVertexes)
447
448         if (newEnergy < self._currentEnergy) or (math.exp(-(newEnergy-self._currentEnergy)/temperature) >= random.random
449             ↪ ()):
450             self._vertexes = newVertexes
451             self._currentEnergy = newEnergy
452             movedVertex = True
453
454     return movedVertex
455
456 def _calculatePathEnergyLambda(self, vlambda):
457     """
458     calculate the energy when lambda is moved.
459     """
460
461     return (self._currentEnergy - (self._vlambda * self._currentConstraints) + (vlambda * self._currentConstraints))
462
463 def _calculatePathEnergyVertex(self, vertexes):
464     """
465     calculate the energy when a vertex is moved and returns it.
466     """
467
468     tau, u, spline, splineD1, splineD2, splineD3, curv, tors, arcLength, polLength = self._splinePoints(vertexes)
469     if self._useArcLen:
470         length = arcLength
471     else:
472         length = polLength
473
474     constraints = self._calculateConstraints(spline)#this is bottleneck
475     maxCurvatureLength = self._calculateMaxCurvatureLength(length, curv, tors)
476
477     energy = maxCurvatureLength + self._vlambda * constraints
478
479     return (energy, maxCurvatureLength, constraints)
480
481 def _calculatePathEnergyVertexPro(self, vertexes):
482     """
483     calculate the energy when a vertex is moved and returns it.
484     """
485
486     tau, u, spline, splineD1, splineD2, splineD3, curv, tors, arcLength, polLength = self._splinePoints(vertexes)
487     if self._useArcLen:
488

```

```

482         length = arcLength
483     else:
484         length = polLength
485
486     energy = self._calculateMaxCurvatureLength(length, curv, tors)
487
488     return energy
489
490     def _calculatePolyLength(self, vertexes):
491         length = 0.
492         for i in range(1, len(vertexes)):
493             length += sp.spatial.distance.euclidean(vertexes[i-1], vertexes[i])
494             #length += np.linalg.norm(np.subtract(vertexes[i], vertexes[i-1]))
495
496     return length
497
498     def _calculateMaxCurvatureLength(self, length, curv, tors):
499         normLength = length/self._initialLength * 100 #for making the ratio independent of the initial length
500
501         maxCurvature = 0.
502         maxTorsion = 0.
503         for i in range(0, len(curv)):
504             currCurv = curv[i]
505             currTors = abs(tors[i])
506             if currCurv > maxCurvature:
507                 maxCurvature = currCurv
508             if currTors > maxTorsion:
509                 maxTorsion = currTors
510
511         return self._ratioCurvTorsLen[0]*maxCurvature + self._ratioCurvTorsLen[1]*maxTorsion + self._ratioCurvTorsLen[2]*
512             ↪ normLength
513
514     def _calculateConstraints(self, spline):
515         """
516             calculate the constraints function. Is the ratio of the points
517             of the calculated spline that are inside obstacles respect the
518             total number of points of the spline.
519         """
520         pointsInside = 0
521         for p in spline:
522             if self._polyhedronsContainer.pointInsidePolyhedron(p):
523                 pointsInside = pointsInside + 1
524
525         constraints = pointsInside / len(spline)
526
527         return constraints
528
529     def _newPathFree(self, newVertexes):
530         free = True
531
532         if self._bsplineDegree == 2:
533             for toEval in range(2, len(newVertexes)):
534                 if self._polyhedronsContainer.triangleIntersectsPolyhedrons(newVertexes[toEval-2], newVertexes[toEval-1],
535                     ↪ newVertexes[toEval]):
536                     free = False
537                     break
538
539         elif self._bsplineDegree == 3:
540             for toEval in range(3, len(newVertexes)):
541                 if self._polyhedronsContainer.convexHullIntersectsPolyhedrons([newVertexes[toEval-3], newVertexes[toEval-2],
542                     ↪ newVertexes[toEval-1], newVertexes[toEval]]):
543                     free = False
544                     break
545
546         elif self._bsplineDegree == 4:
547             for toEval in range(4, len(newVertexes)):
548                 if self._polyhedronsContainer.convexHullIntersectsPolyhedrons([newVertexes[toEval-4], newVertexes[toEval-3],
549                     ↪ newVertexes[toEval-2], newVertexes[toEval-1], newVertexes[toEval]]):
550                     free = False
551                     break
552
553         return free

```

### A.1.3 *plotter.py*

```

1 | import numpy as np

```

```

2 | import scipy as sp
3 | import scipy.interpolate
4 | import scipy.spatial
5 | import pickle
6 | import vtk
7 | import vtk.util.colors
8 | import math
9 | import warnings
10| warnings.filterwarnings("error")
11|
12| class Plotter:
13|     COLOR_BG = vtk.util.colors.light_grey
14|     COLOR_BG_PLOT = vtk.util.colors.ghost_white
15|     #vtk.util.colors.ivory
16|     COLOR_OBSTACLE = vtk.util.colors.banana
17|     COLOR_SITES = vtk.util.colors.cobalt
18|     COLOR_PATH = vtk.util.colors.brick
19|     COLOR_CONTROL_POINTS = vtk.util.colors.tomato
20|     COLOR_CONTROL_POLIG = vtk.util.colors.mint
21|     COLOR_GRAPH = vtk.util.colors.sepia
22|     COLOR_PLOT_CURV = vtk.util.colors.blue
23|     COLOR_PLOT_TORS = vtk.util.colors.red
24|     COLOR_LABELS = vtk.util.colors.blue
25|     COLOR_LENGTH = vtk.util.colors.red
26|
27|     _DEFAULT_LINE_THICKNESS = 0.0005
28|     _DEFAULT_POINT_THICKNESS = 0.002
29|     _DEFAULT_BSPLINE_THICKNESS = 0.001
30|
31| class KeyPressInteractorStyle(vtk.vtkInteractorStyleUnicam):
32|     _screenshotFile = "/tmp/screenshot.png"
33|     _cameraFile = "/tmp/cameraData.dat"
34|     _cameraFile2 = "/tmp/cameraData2.dat"
35|     def __init__(self, parent=None):
36|         self.AddObserver("KeyPressEvent", self._keyPressEvent)
37|         self.AddObserver("RightButtonPressEvent", self._mousePressEvent)
38|         #super(KeyPressInteractorStyle, self).__init__()
39|
40|     def SetCamera(self, camera):
41|         self._camera = camera
42|
43|     def SetRenderer(self, renderer):
44|         self._renderer = renderer
45|
46|     def SetRenderWindow(self, renderWindow):
47|         self._renderWindow = renderWindow
48|
49|     def _keyPressEvent(self, obj, event):
50|         if obj.GetInteractor().GetKeySym() == "l":
51|             print("Scene screenshot in "+self._screenshotFile)
52|             w2if = vtk.vtkWindowToImageFilter()
53|             w2if.SetInput(self._renderWindow)
54|             w2if.Update()
55|
56|             writer = vtk.vtkPNGWriter()
57|             writer.SetFileName(self._screenshotFile)
58|             writer.SetInputData(w2if.GetOutput())
59|             writer.Write()
60|
61|         elif obj.GetInteractor().GetKeySym() == "c":
62|             print("Save camera data in "+self._cameraFile)
63|             record = {}
64|             record['position'] = self._cameraGetPosition()
65|             record['focalPoint'] = self._cameraGetFocalPoint()
66|             record['viewAngle'] = self._cameraGetViewAngle()
67|             record['viewUp'] = self._cameraGetViewUp()
68|             record['clippingRange'] = self._cameraGetClippingRange()
69|
70|             with open(self._cameraFile, 'wb') as f:
71|                 pickle.dump(record, f)
72|
73|         elif obj.GetInteractor().GetKeySym() == "v":
74|             print("Restore camera data from "+self._cameraFile)
75|
76|             with open(self._cameraFile, 'rb') as f:
77|                 record = pickle.load(f)
78|
79|                 self._camera.SetPosition(record['position'])
80|                 self._camera.SetFocalPoint(record['focalPoint'])
81|                 self._camera.SetViewAngle(record['viewAngle'])
82|                 self._camera.SetViewUp(record['viewUp'])
83|                 self._camera.SetClippingRange(record['clippingRange'])

```

```

84         self._renderWindow.Render()
85
86     elif obj.GetInteractor().GetKeySym() == "b":
87         print("Restore camera data from "+self._cameraFile2)
88
89     with open(self._cameraFile2, 'rb') as f:
90         record = pickle.load(f)
91
92         self._camera.SetPosition(record['position'])
93         self._camera.SetFocalPoint(record['focalPoint'])
94         self._camera.SetViewAngle(record['viewAngle'])
95         self._camera.SetViewUp(record['viewUp'])
96         self._camera.SetClippingRange(record['clippingRange'])
97
98         self._renderWindow.Render()
99
100
101    self.OnKeyPress()
102
103    def _mousePressEvent(self, obj, event):
104        clickPos = obj.GetInteractor().GetEventPosition()
105        picker = vtk.vtkPropPicker()
106        picker.Pick(clickPos[0], clickPos[1], 0, self._renderer)
107        pos = picker.GetPickPosition()
108        print(pos)
109
110
111    class KeyPressContextInteractorStyle(vtk.vtkContextInteractorStyle):
112        _screenshotFile = "/tmp/screenshot.png"
113
114        def __init__(self, parent=None):
115            self.AddObserver("KeyPressEvent", self._keyPressEvent)
116
117        def SetRenderWindow(self, renderWindow):
118            self._renderWindow = renderWindow
119
120        def _keyPressEvent(self, obj, event):
121            if obj.GetInteractor().GetKeySym() == "l":
122                print("Plot screenshot in "+self._screenshotFile)
123                w2if = vtk.vtkWindowToImageFilter()
124                w2if.SetInput(self._renderWindow)
125                w2if.Update()
126
127                writer = vtk.vtkPNGWriter()
128                writer.SetFileName(self._screenshotFile)
129                writer.SetInputData(w2if.GetOutput())
130                writer.Update()
131
132
133        def __init__(self):
134            self._rendererScene = vtk.vtkRenderer()
135            self._rendererScene.SetBackground(self.COLOR_BG)
136
137            self._renderWindowScene = vtk.vtkRenderWindow()
138            self._renderWindowScene.AddRenderer(self._rendererScene)
139            self._renderWindowInteractor = vtk.vtkRenderWindowInteractor()
140            self._renderWindowInteractor.SetRenderWindow(self._renderWindowScene)
141            #self._interactorStyle = vtk.vtkInteractorStyleUnicam()
142            self._interactorStyle = self.KeyPressInteractorStyle()
143            self._interactorStyle.SetCamera(self._rendererScene.GetActiveCamera())
144            self._interactorStyle.SetRenderer(self._rendererScene)
145            self._interactorStyle.SetRenderWindow(self._renderWindowScene)
146
147            self._contextViewPlotCurv = vtk.vtkContextView()
148            self._contextViewPlotCurv.GetRenderer().SetBackground(self.COLOR_BG_PLOT)
149
150            self._contextInteractorStyleCurv = self.KeyPressContextInteractorStyle()
151            self._contextInteractorStyleCurv.SetRenderWindow(self._contextViewPlotCurv.GetRenderWindow())
152
153            self._chartXYCurv = vtk.vtkChartXY()
154            self._contextViewPlotCurv.GetScene().AddItem(self._chartXYCurv)
155            self._chartYCurv.SetShowLegend(True)
156            self._chartXYCurv.GetAxis(vtk.vtkAxis.LEFT).SetTitle("")
157            self._chartXYCurv.GetAxis(vtk.vtkAxis.BOTTOM).SetTitle("")
158
159            self._contextViewPlotTors = vtk.vtkContextView()
160            self._contextViewPlotTors.GetRenderer().SetBackground(self.COLOR_BG_PLOT)
161
162            self._contextInteractorStyleTors = self.KeyPressContextInteractorStyle()
163            self._contextInteractorStyleTors.SetRenderWindow(self._contextViewPlotTors.GetRenderWindow())
164
165

```

```

166     self._chartXYTors = vtk.vtkChartXY()
167     self._contextViewPlotTors.GetScene().AddItem(self._chartXYTors)
168     self._chartXYTors.SetShowLegend(True)
169     self._chartXYTors.GetAxis(vtk.vtkAxis.LEFT).SetTitle("")
170     self._chartXYTors.GetAxis(vtk.vtkAxis.BOTTOM).SetTitle("")
171
172     self._textActor = vtk.vtkTextActor()
173     self._textActor.GetTextProperty().SetColor(self.COLOR_LENGTH)
174
175     self._addedBSpline = False
176
177     def draw(self):
178         self._renderWindowInteractor.Initialize()
179         self._renderWindowInteractor.SetInteractorStyle(self._interactorStyle)
180
181         axes = vtk.vtkAxesActor()
182         widget = vtk.vtkOrientationMarkerWidget()
183         widget.SetOutlineColor(0.9300, 0.5700, 0.1300)
184         widget.SetOrientationMarker(axes)
185         widget.SetInteractor(self._renderWindowInteractor)
186         #widget.SetViewport(0.0, 0.0, 0.1, 0.1)
187         widget.SetViewport(0.0, 0.0, 0.2, 0.4)
188         widget.SetEnabled(True)
189         widget.InteractiveOn()
190
191         textWidget = vtk.vtkTextWidget()
192
193         textRepresentation = vtk.vtkTextRepresentation()
194         textRepresentation.GetPositionCoordinate().SetValue(.0,.0 )
195         textRepresentation.GetPosition2Coordinate().SetValue(.3,.04 )
196         textWidget.SetRepresentation(textRepresentation)
197
198         textWidget.SetInteractor(self._renderWindowInteractor)
199         textWidget.SetTextActor(self._textActor)
200         textWidget.SelectableOff()
201         textWidget.On()
202
203         self._rendererScene.ResetCamera()
204         camPos = self._rendererScene.GetActiveCamera().GetPosition()
205         self._rendererScene.GetActiveCamera().SetPosition((camPos[2],camPos[1],camPos[0]))
206         self._rendererScene.GetActiveCamera().SetViewUp((0.0,0.0,1.0))
207         self._rendererScene.GetActiveCamera().Zoom(1.4)
208
209         self._renderWindowScene.Render()
210
211     if self._addedBSpline:
212         self._contextViewPlotCurv.GetRenderWindow().SetMultiSamples(0)
213         self._contextViewPlotCurv.GetInteractor().Initialize()
214         self._contextViewPlotCurv.GetInteractor().SetInteractorStyle(self._contextInteractorStyleCurv)
215         #self._contextViewPlotCurv.GetInteractor().Start()
216
217         self._contextViewPlotTors.GetRenderWindow().SetMultiSamples(0)
218         self._contextViewPlotTors.GetInteractor().Initialize()
219         self._contextViewPlotTors.GetInteractor().SetInteractorStyle(self._contextInteractorStyleTors)
220         self._contextViewPlotTors.GetInteractor().Start()
221     else:
222         self._renderWindowInteractor.Start()
223
224
225     def addTetrahedron(self, vertexes, color):
226         vtkPoints = vtk.vtkPoints()
227         vtkPoints.InsertNextPoint(vertexes[0][0], vertexes[0][1], vertexes[0][2])
228         vtkPoints.InsertNextPoint(vertexes[1][0], vertexes[1][1], vertexes[1][2])
229         vtkPoints.InsertNextPoint(vertexes[2][0], vertexes[2][1], vertexes[2][2])
230         vtkPoints.InsertNextPoint(vertexes[3][0], vertexes[3][1], vertexes[3][2])
231
232         unstructuredGrid = vtk.vtkUnstructuredGrid()
233         unstructuredGrid.SetPoints(vtkPoints)
234         unstructuredGrid.InsertNextCell(vtk.VTK_TETRA, 4, range(4))
235
236         mapper = vtk.vtkDataSetMapper()
237         mapper.SetInputData(unstructuredGrid)
238
239         actor = vtk.vtkActor()
240         actor.SetMapper(mapper)
241         actor.GetProperty().SetColor(color)
242
243         self._rendererScene.AddActor(actor)
244
245     def addTriangles(self, triangles, color):
246         vtkPoints = vtk.vtkPoints()
247         idPoint = 0

```

```

248     allIdsTriangle = []
249
250     for triangle in triangles:
251         idsTriangle = []
252
253         for point in triangle:
254             vtkPoints.InsertNextPoint(point[0], point[1], point[2])
255             idsTriangle.append(idPoint)
256             idPoint += 1
257
258         allIdsTriangle.append(idsTriangle)
259
260     unstructuredGrid = vtk.vtkUnstructuredGrid()
261     unstructuredGrid.SetPoints(vtkPoints)
262     for idsTriangle in allIdsTriangle:
263         unstructuredGrid.InsertNextCell(vtk.VTK_TRIANGLE, 3, idsTriangle)
264
265     mapper = vtk.vtkDataSetMapper()
266     mapper.SetInputData(unstructuredGrid)
267
268     actor = vtk.vtkActor()
269     actor.SetMapper(mapper)
270     actor.GetProperty().SetColor(color)
271
272     self._rendererScene.AddActor(actor)
273
274 def addPolyLine(self, points, color, thick=False, thickness=_DEFAULT_LINE_THICKNESS):
275     vtkPoints = vtk.vtkPoints()
276     for point in points:
277         vtkPoints.InsertNextPoint(point[0], point[1], point[2])
278
279     if thick:
280         cellArray = vtk.vtkCellArray()
281         cellArray.InsertNextCell(len(points))
282         for i in range(len(points)):
283             cellArray.InsertCellPoint(i)
284
285         polyData = vtk.vtkPolyData()
286         polyData.SetPoints(vtkPoints)
287         polyData.SetLines(cellArray)
288
289         tubeFilter = vtk.vtkTubeFilter()
290         tubeFilter.SetNumberOfSides(8)
291         tubeFilter.SetInputData(polyData)
292         tubeFilter.SetRadius(thickness)
293         tubeFilter.Update()
294
295         mapper = vtk.vtkPolyDataMapper()
296         mapper.SetInputConnection(tubeFilter.GetOutputPort())
297
298     else:
299         unstructuredGrid = vtk.vtkUnstructuredGrid()
300         unstructuredGrid.SetPoints(vtkPoints)
301         for i in range(1, len(points)):
302             unstructuredGrid.InsertNextCell(vtk.VTK_LINE, 2, [i-1, i])
303
304         mapper = vtk.vtkDataSetMapper()
305         mapper.SetInputData(unstructuredGrid)
306
307         actor = vtk.vtkActor()
308         actor.SetMapper(mapper)
309         actor.GetProperty().SetColor(color)
310
311         self._rendererScene.AddActor(actor)
312
313 def addPoints(self, points, color, thick=False, thickness=_DEFAULT_POINT_THICKNESS):
314     vtkPoints = vtk.vtkPoints()
315     for point in points:
316         vtkPoints.InsertNextPoint(point[0], point[1], point[2])
317
318     pointsPolyData = vtk.vtkPolyData()
319     pointsPolyData.SetPoints(vtkPoints)
320
321     if thick:
322         sphereSource = vtk.vtkSphereSource()
323         sphereSource.SetRadius(thickness)
324
325         glyph3D = vtk.vtkGlyph3D()
326         glyph3D.SetSourceConnection(sphereSource.GetOutputPort())
327         glyph3D.SetInputData(pointsPolyData)
328         glyph3D.Update()
329

```

```

330     mapper = vtk.vtkPolyDataMapper()
331     mapper.SetInputConnection(glyph3D.GetOutputPort())
332 else:
333     vertexFilter = vtk.vtkVertexGlyphFilter()
334     vertexFilter.SetInputData(pointsPolyData)
335     vertexFilter.Update()
336
337     mapper = vtk.vtkPolyDataMapper()
338     mapper.SetInputData(vertexFilter.GetOutput())
339
340     actor = vtk.vtkActor()
341     actor.SetMapper(mapper)
342     actor.GetProperty().SetColor(color)
343
344     self._rendererScene.AddActor(actor)
345
346 def addBSpline(self, path, degree, color, thick=False, thickness=_DEFAULT_BSPLINE_THICKNESS):
347     self._addedBSpline = True
348
349     tau, u, spline, splineD1, splineD2, splineD3, curv, tors, arcLength, polLength = path.splinePoints()
350
351     self._textActor.SetInput("Length: "+str(arcLength))
352
353     numIntervals = len(tau)-1
354
355     curvPlotActor = vtk.vtkXYPlotActor()
356     curvPlotActor.setTitle("Curvature")
357     curvPlotActor.setXTitle("")
358     curvPlotActor.setYTitle("")
359     curvPlotActor.SetXValuesToIndex()
360
361     torsPlotActor = vtk.vtkXYPlotActor()
362     torsPlotActor.setTitle("Torsion")
363     torsPlotActor.setXTitle("")
364     torsPlotActor.setYTitle("")
365     torsPlotActor.SetXValuesToIndex()
366
367     uArrays = []
368     curvArrays = []
369     torsArrays = []
370     for i in range(numIntervals):
371         uArrays.append(vtk.vtkDoubleArray())
372         uArrays[i].SetName("t")
373
374         curvArrays.append(vtk.vtkDoubleArray())
375         curvArrays[i].SetName("Curvature")
376
377         torsArrays.append(vtk.vtkDoubleArray())
378         torsArrays[i].SetName("Torsion")
379
380     curvTorsArray = vtk.vtkDoubleArray()
381
382     #minCurv = minTors = minNdx2d = float("inf")
383     #maxCurv = maxTors = float("-inf")
384
385     for i in range(len(u)):
386         for j in range(numIntervals):
387             if u[i] >= tau[j] and u[i] < tau[j+1]:
388                 break
389
390             uArrays[j].InsertNextValue(u[i])
391             curvArrays[j].InsertNextValue(curv[i])
392             torsArrays[j].InsertNextValue(tors[i])
393
394             curvTorsArray.InsertNextValue(curv[i])# + abs(tors[i]))
395
396     #print("minCurv: {:e}; maxCurv: {:e}; minTors: {:e}; maxTors: {:e}; minNdx2d: {:e} ".format(minCurv, maxCurv, minTors
397     #                                     , maxTors, minNdx2d))
398
399     for inter in range(numIntervals):
400         plotTable = vtk.vtkTable()
401         plotTable.AddColumn(uArrays[inter])
402         plotTable.AddColumn(curvArrays[inter])
403         plotTable.AddColumn(torsArrays[inter])
404
405         points = self._chartXYCurv.AddPlot(vtk.vtkChart.LINE)
406         points.SetInputData(plotTable, 0, 1)
407         points.SetColor(self.COLOR_PLOT_CURV[0], self.COLOR_PLOT_CURV[1], self.COLOR_PLOT_CURV[2])
408         points.SetWidth(1.0)
409         if inter > 0:
410             points.SetLegendVisibility(False)

```

```

411     points = self._chartXYTors.AddPlot(vtk.vtkChart.LINE)
412     points.SetInputData(plotTable, 0, 2)
413     points.SetColor(self.COLOR_PLOT_TORS[0], self.COLOR_PLOT_TORS[1], self.COLOR_PLOT_TORS[2])
414     points.SetWidth(1.0)
415     if inter > 0:
416         points.SetLegendVisibility(False)
417
418
419     vtkPoints = vtk.vtkPoints()
420     for point in spline:
421         vtkPoints.InsertNextPoint(point[0], point[1], point[2])
422
423     polyDataLabelP = vtk.vtkPolyData()
424     polyDataLabelP.SetPoints(vtkPoints)
425
426     labels = vtk.vtkStringArray()
427     labels.SetNumberOfValues(len(spline))
428     labels.SetName("labels")
429     for i in range(len(spline)):
430         if i == 0:
431             labels.SetValue(i, "S")
432         elif i == len(spline)-1:
433             labels.SetValue(i, "E")
434         else:
435             labels.SetValue(i, "")
436
437     polyDataLabelP.GetPointData().AddArray(labels)
438
439     sizes = vtk.vtkIntArray()
440     sizes.SetNumberOfValues(len(spline))
441     sizes.SetName("sizes")
442     for i in range(len(spline)):
443         if i == 0 or i == len(spline)-1:
444             sizes.SetValue(i, 10)
445         else:
446             sizes.SetValue(i, 1)
447
448     polyDataLabelP.GetPointData().AddArray(sizes)
449
450     pointMapper = vtk.vtkPolyDataMapper()
451     pointMapper.SetInputData(polyDataLabelP)
452
453     pointActor = vtk.vtkActor()
454     pointActor.SetMapper(pointMapper)
455
456     pointSetToLabelHierarchyFilter = vtk.vtkPointSetToLabelHierarchy()
457     pointSetToLabelHierarchyFilter.SetInputData(polyDataLabelP)
458     pointSetToLabelHierarchyFilter.SetLabelArrayName("labels")
459     pointSetToLabelHierarchyFilter.SetPriorityArrayName("sizes")
460     pointSetToLabelHierarchyFilter.GetTextProperty().SetColor(self.COLOR_LABELS)
461     pointSetToLabelHierarchyFilter.GetTextProperty().SetFontFamily(15)
462     pointSetToLabelHierarchyFilter.GetTextProperty().SetBold(True)
463     pointSetToLabelHierarchyFilter.Update()
464
465     labelMapper = vtk.vtkLabelPlacementMapper()
466     labelMapper.SetInputConnection(pointSetToLabelHierarchyFilter.GetOutputPort())
467     labelActor = vtk.vtkActor2D()
468     labelActor.SetMapper(labelMapper)
469
470     self._rendererScene.AddActor(labelActor)
471
472     if thick:
473         cellArray = vtk.vtkCellArray()
474         cellArray.InsertNextCell(len(spline))
475         for i in range(len(spline)):
476             cellArray.InsertCellPoint(i)
477
478         polyData = vtk.vtkPolyData()
479         polyData.SetPoints(vtkPoints)
480         polyData.SetLines(cellArray)
481
482         polyData.GetPointData().SetScalars(curvTorsArray)
483
484         tubeFilter = vtk.vtkTubeFilter()
485         tubeFilter.SetNumberOfSides(8)
486         tubeFilter.SetInputData(polyData)
487         tubeFilter.SetRadius(thickness)
488         tubeFilter.Update()
489
490         mapper = vtk.vtkPolyDataMapper()
491         mapper.SetInputConnection(tubeFilter.GetOutputPort())
492

```

```

493     else:
494         unstructuredGrid = vtk.vtkUnstructuredGrid()
495         unstructuredGrid.SetPoints(vtkPoints)
496         for i in range(1, len(spline)):
497             unstructuredGrid.InsertNextCell(vtk.VTK_LINE, 2, [i-1, i])
498
499         unstructuredGrid.GetPointData().SetScalars(curvArray)
500
501         mapper = vtk.vtkDataSetMapper()
502         mapper.SetInputData(unstructuredGrid)
503
504         actor = vtk.vtkActor()
505         actor.SetMapper(mapper)
506         actor.GetProperty().SetColor(color)
507
508         self._rendererScene.AddActor(actor)
509
510
511         #self.addPolyLine(list(zip(out[0], out[1], out[2])), color, thick, thickness)
512
513     def addBSplineDEPRECATED(self, controlPolygon, degree, color, thick=False, thickness=_DEFAULT_BSPLINE_THICKNESS):
514         x = controlPolygon[:,0]
515         y = controlPolygon[:,1]
516         z = controlPolygon[:,2]
517
518         polLen = 0.
519         for i in range(1, len(controlPolygon)):
520             polLen += sp.spatial.distance.euclidean(controlPolygon[i-1], controlPolygon[i])
521
522         t = range(len(controlPolygon))
523         ipl_t = np.linspace(0.0, len(controlPolygon) - 1, max(polLen*100,100))
524
525         x_tup = sp.interpolate.splrep(t, x, k = degree)
526         y_tup = sp.interpolate.splrep(t, y, k = degree)
527         z_tup = sp.interpolate.splrep(t, z, k = degree)
528
529         x_list = list(x_tup)
530         xl = x.tolist()
531         x_list[1] = xl + [0.0, 0.0, 0.0, 0.0]
532
533         y_list = list(y_tup)
534         yl = y.tolist()
535         y_list[1] = yl + [0.0, 0.0, 0.0, 0.0]
536
537         z_list = list(z_tup)
538         zl = z.tolist()
539         z_list[1] = zl + [0.0, 0.0, 0.0, 0.0]
540
541         x_i = sp.interpolate.splev(ipl_t, x_list)
542         y_i = sp.interpolate.splev(ipl_t, y_list)
543         z_i = sp.interpolate.splev(ipl_t, z_list)
544
545         self.addPolyLine(list(zip(x_i, y_i, z_i)), color, thick, thickness)
546
547     def addGraph(self, graph, color):
548         vtkPoints = vtk.vtkPoints()
549         vtkId = 0
550         graph2VtkId = {}
551
552         for node in graph.nodes():
553             vtkPoints.InsertNextPoint(graph.node[node]['coord'][0], graph.node[node]['coord'][1], graph.node[node]['coord']
554             ↪ ]2[])
554             graph2VtkId[node] = vtkId
555             vtkId += 1
556
557         unstructuredGrid = vtk.vtkUnstructuredGrid()
558         unstructuredGrid.SetPoints(vtkPoints)
559
560         for edge in graph.edges():
561             unstructuredGrid.InsertNextCell(vtk.VTK_LINE, 2, [graph2VtkId[edge[0]], graph2VtkId[edge[1]]])
562
563         mapper = vtk.vtkDataSetMapper()
564         mapper.SetInputData(unstructuredGrid)
565
566         actor = vtk.vtkActor()
567         actor.SetMapper(mapper)
568         actor.GetProperty().SetColor(color)
569
570         self._rendererScene.AddActor(actor)

```

#### A.1.4 polyhedronsContainer.py

```

1 import numpy as np
2 import scipy as sp
3 import scipy.spatial
4 import polyhedron
5 import parallelepiped
6
7 class PolyhedronsContainer:
8     def __init__(self):
9         self._polyhedrons = []
10        self._hasBoundingBox = False
11        self._boundingBoxA = None
12        self._boundingBoxB = None
13
14    @property
15    def polyhedrons(self):
16        return self._polyhedrons
17
18    @property
19    def hasBoundingBox(self):
20        return self._hasBoundingBox
21
22    @hasBoundingBox.setter
23    def hasBoundingBox(self, value):
24        self._hasBoundingBox = value
25
26    @property
27    def boundingBoxA(self):
28        return self._boundingBoxA
29
30    @boundingBoxA.setter
31    def boundingBoxA(self, value):
32        self._boundingBoxA = value
33
34    @property
35    def boundingBoxB(self):
36        return self._boundingBoxB
37
38    @boundingBoxB.setter
39    def boundingBoxB(self, value):
40        self._boundingBoxB = value
41
42    def addPolyhedron(self, polyhedron):
43        self._polyhedrons.append(polyhedron)
44
45    def addBoundingBox(self, a, b, maxEmptyArea, invisible):
46        self._hasBoundingBox = True
47        self._boundingBoxA = a
48        self._boundingBoxB = b
49
50        self.addPolyhedron(parallelepiped.Parallelepiped(a=a, b=b, invisible=invisible, maxEmptyArea=maxEmptyArea,
51                                                       ↪ boundingBox=True))
52
53    def pointInsidePolyhedron(self, p):
54        inside = False
55
56        if self._hasBoundingBox:
57            if (p < self._boundingBoxA).any() or (p > self._boundingBoxB).any():
58                inside = True
59
60            if not inside:
61                for polyhedron in self._polyhedrons:
62                    if (not polyhedron.isBoundingBox()) and polyhedron.hasPointInside(p):
63                        inside = True
64                        break
65
66
67    def segmentIntersectPolyhedrons(self, a, b, intersectionMargin = 0.):
68        intersect = False
69
70        if self._hasBoundingBox:
71            if ((a <= self._boundingBoxA).any() or (a > self._boundingBoxB).any() or (b <= self._boundingBoxA).any() or (b > self.
72                                                       ↪ _boundingBoxB).any()):
73                intersect = True
74
75            if not intersect:
76                minS = np.array([min(a[0],b[0]),min(a[1],b[1]),min(a[2],b[2])])

```

```

77         for polyhedron in self._polyhedrons:
78             if polyhedron.intersectSegment(a,b,minS,maxS, intersectionMargin=intersectionMargin)[0]:
79                 intersect = True
80                 break
81
82     return intersect
83
84 def triangleIntersectPolyhedrons(self, a, b, c):
85     triangle = polyhedron.Polyhedron(faces=np.array([[a,b,c]]), distributePoints = False)
86     intersect = False
87     result = np.array([[]])
88     for currPolyhedron in self._polyhedrons:
89         currIntersect,currResult = currPolyhedron.intersectPathTriple(triangle)
90         if currIntersect and (not intersect or (currResult[1] > result[1])):
91             intersect = True
92             result = currResult
93
94     return (intersect, result)
95
96 def convexHullIntersectsPolyhedrons(self, vertexes):
97     convHull = sp.spatial.ConvexHull(vertexes, qhull_options="QJ Pp")
98     for simplex in convHull.simplices:
99         if self.triangleIntersectPolyhedrons(convHull.points[simplex[0]], convHull.points[simplex[1]], convHull.points[
100             ↪ simplex[2]])[0]:
101             return True
102
103     return False

```

### A.1.5 *polyhedron.py*

```

1 import numpy as np
2 import scipy as sp
3 import scipy.spatial
4 import math
5 import xml.etree.cElementTree as ET
6
7 class Polyhedron:
8     def __init__(self, faces, invisible=False, distributePoints=True, maxEmptyArea=0.1, boundingBox=False):
9         """
10         can be composed only by combined triangles
11         faces -> an np.array of triangular faces
12         if invisible=True when plot will be called it will be useless
13         """
14         self._faces = faces
15         self._invisible = invisible
16         self._boundingBox = boundingBox
17
18         self._minV = np.array([float('inf'),float('inf'),float('inf')])
19         self._maxV = np.array([float('-inf'),float('-inf'),float('-inf')])
20         for face in self._faces:
21             for vertex in face:
22                 for i in range(len(vertex)):
23                     if vertex[i] < self._minV[i]:
24                         self._minV[i] = vertex[i]
25
26                     for i in range(len(vertex)):
27                         if vertex[i] > self._maxV[i]:
28                             self._maxV[i] = vertex[i]
29
30             if distributePoints:
31                 self.distributePoints(maxEmptyArea)
32             else:
33                 self._allPoints = np.array([])
34
35     @property
36     def allPoints(self):
37         return self._allPoints
38
39     @property
40     def minV(self):
41         return self._minV
42
43     @property
44     def maxV(self):
45         return self._maxV
46

```

```

47     def isBoundingBox(self):
48         return self._boundingBox
49
50     def _area(self, triangle):
51         a = np.linalg.norm(triangle[1]-triangle[0])
52         b = np.linalg.norm(triangle[2]-triangle[1])
53         c = np.linalg.norm(triangle[0]-triangle[2])
54         s = (a+b+c) / 2.
55         return math.sqrt(s * (s-a) * (s-b) *(s-c))
56
57     _comb2 = lambda self,a,b: 0.5*a + 0.5*b
58     #_comb3 = lambda self,a,b,c: 0.33*a + 0.33*b + 0.33*c
59
60     def distributePoints(self, maxEmptyArea):
61         allPoints = []
62         triangles = []
63
64         for face in self._faces:
65             triangles.append(face)
66
67         while triangles:
68             triangle = triangles.pop(0)
69             a = triangle[0]
70             b = triangle[1]
71             c = triangle[2]
72             if not any((a == x).all() for x in allPoints):
73                 allPoints.append(a)
74             if not any((b == x).all() for x in allPoints):
75                 allPoints.append(b)
76             if not any((c == x).all() for x in allPoints):
77                 allPoints.append(c)
78             if (self._area(triangle) > maxEmptyArea):
79                 ab = self._comb2(a,b)
80                 bc = self._comb2(b,c)
81                 ca = self._comb2(c,a)
82                 #abc = self._comb3(a,b,c)
83
84                 triangles.append(np.array([a,ab,ca]))
85                 triangles.append(np.array([ab,b,bc]))
86                 triangles.append(np.array([bc,c,ca]))
87                 triangles.append(np.array([ab,bc,ca]))
88                 #triangles.append(np.array([a,ab,abc]))
89                 #triangles.append(np.array([ab,b,abc]))
90                 #triangles.append(np.array([b,bc,abc]))
91                 #triangles.append(np.array([bc,c,abc]))
92                 #triangles.append(np.array([c,ca,abc]))
93                 #triangles.append(np.array([ca,a,abc]))
94
95         self._allPoints = np.array(allPoints)
96
97     def hasPointInside(self, p):
98         """
99             check if a point is inside the convex hull of obstacle vertexes
100        """
101        outside = True
102        if (p>self._minV).all() and (p<self._maxV).all():
103            vertexes = [p]
104            for triangle in self._faces:
105                vertexes.append(triangle[0])
106                vertexes.append(triangle[1])
107                vertexes.append(triangle[2])
108
109            chull = sp.spatial.ConvexHull(np.array(vertexes))
110            outside = False
111            for vertex in chull.vertices:
112                if (p == chull.points[vertex]).all():
113                    outside = True
114                    break
115                for simplex in chull.simplices:
116                    if (p == chull.points[simplex[0]]).all() or (p == chull.points[simplex[1]]).all() or (p == chull.points[
117                        #      if (p == chull.points[simplex[0]]).all() or (p == chull.points[simplex[1]]).all() or (p == chull.points[
118                            #          ↪ simplex[2]].all()):
119                            #          outside = True
120                            #          break
121
122        return not outside
123
124    def intersectSegment(self, a, b, minS=None, maxS=None, intersectionMargin=0.):
125        if minS is None or maxS is None:
126            minS = np.array([min(a[0],b[0]),min(a[1],b[1]),min(a[2],b[2]))]
127            maxS = np.array([max(a[0],b[0]),max(a[1],b[1]),max(a[2],b[2]))]
128
129        if not ((self._minV > maxS).any() or (self._maxV < minS).any()):

```

```

128     for triangle in self._faces:
129         #solve {
130             #      a+k(b-a) = v*triangle[0] + w*triangle[1] + s*triangle[2]
131             #      v+w+s = 1
132             #
133         # for variables k, v, w, s
134
135         #simplified in
136         #      a+k(b-a) = (1-w-s)*triangle[0] + w*triangle[1] + s*triangle[2]
137         # for variables k, w, s
138
139         diffba = b-a
140         difft0t1 = triangle[0] - triangle[1]
141         difft0t2 = triangle[0] - triangle[2]
142         difft0a = triangle[0] - a
143
144         A = np.array([
145             [diffba[0], difft0t1[0], difft0t2[0]],
146             [diffba[1], difft0t1[1], difft0t2[1]],
147             [diffba[2], difft0t1[2], difft0t2[2]]])
148         B = np.array([difft0a[0], difft0a[1], difft0a[2]])
149
150     try:
151         x = np.linalg.solve(A,B)
152         # check (with margins) if
153         #      0 < k < 1,
154         #      w > 0
155         #      s > 0
156         #      w+s < 1
157         if (x[0] >= 0. - intersectionMargin) and (x[0] <= 1. + intersectionMargin) and (x[1] >= 0. -
158             ↪ intersectionMargin) and (x[2] >= 0. - intersectionMargin) and (x[1]+x[2] <= 1. +
159             ↪ intersectionMargin):
160             return (True, x)
161     except np.linalg.LinAlgError:
162         pass
163
164     return (False,np.array([]))
165
166 def intersectPolyhedron(self, polyhedron):
167     """alert, not case of one polyhedron inside other"""
168     if not ((self._minV > polyhedron.maxV).any() or (self._maxV < polyhedron.minV).any()):
169         for otherFace in polyhedron._faces:
170             for myFace in self._faces:
171                 if (
172                     self.intersectSegment(otherFace[0],otherFace[1])[0] or
173                     self.intersectSegment(otherFace[1],otherFace[2])[0] or
174                     self.intersectSegment(otherFace[2],otherFace[0])[0] or
175                     polyhedron.intersectSegment(myFace[0], myFace[1])[0] or
176                     polyhedron.intersectSegment(myFace[1], myFace[2])[0] or
177                     polyhedron.intersectSegment(myFace[2], myFace[0])[0]):
178                 return True
179
180     return False
181
182 def intersectPathTriple(self, triple):
183     """alert, not case of one polyhedron inside other, and only
184     check if the segments of self intersect the triple."""
185     intersect = False
186     result = np.array([])
187
188     if not ((self._minV > triple.maxV).any() or (self._maxV < triple.minV).any()):
189         for myFace in self._faces:
190             intersect1, result1 = triple.intersectSegment(myFace[0], myFace[1])
191             intersect2, result2 = triple.intersectSegment(myFace[1], myFace[2])
192             intersect3, result3 = triple.intersectSegment(myFace[2], myFace[0])
193
194             if intersect1:
195                 intersect = True
196                 result = result1
197             if intersect2 and (not intersect or (result2[1] > result[1])):
198                 intersect = True
199                 result = result2
200             if intersect3 and (not intersect or (result3[1] > result[1])):
201                 intersect = True
202                 result = result3
203
204     return intersect, result
205
206 def plotAllPoints(self, plotter):
207     if self._allPoints.size > 0:
208         plotter.addPoints(self._allPoints, plotter.COLOR_SITES)
209
210 def plot(self, plotter):
211

```

```

208     if self._invisible == False:
209         plotter.addTriangles(self._faces, plotter.COLOR_OBSTACLE)
210
211     def extractXmlTree(self, root):
212         xmlPolyhedron = ET.SubElement(root, 'polyhedron', invisible=str(self._invisible), boundingBox=str(self._boundingBox))
213         for face in self._faces:
214             xmlFace = ET.SubElement(xmlPolyhedron, 'face')
215             for vertex in face:
216                 xmlVertex = ET.SubElement(xmlFace, 'vertex', x=str(vertex[0]), y=str(vertex[1]), z=str(vertex[2]))

```

### A.1.6 compositePolyhedron.py

```

1 import numpy as np
2 import polyhedron
3
4 class CompositePolyhedron(polyhedron.Polyhedron):
5     def __init__(self, components):
6         self._components = components
7
8         self._boundingBox = False
9
10        self._minV = np.array([float('inf'), float('inf'), float('inf')])
11        self._maxV = np.array([float('-inf'), float('-inf'), float('-inf')])
12
13        for component in self._components:
14            for i in range(3):
15                if component.minV[i] < self._minV[i]:
16                    self._minV[i] = component.minV[i]
17
18                if component.maxV[i] > self._maxV[i]:
19                    self._maxV[i] = component.maxV[i]
20
21    @property
22    def allPoints(self):
23        allPoints = []
24        for component in self._components:
25            allPoints.extend(list(component.allPoints))
26
27        return np.array(allPoints)
28
29    @property
30    def minV(self):
31        return self._minV
32
33    @property
34    def maxV(self):
35        return self._maxV
36
37
38    def distributePoints(self, maxEmptyArea):
39        for component in self._components:
40            component.distributePoints(maxEmptyArea)
41
42    def hasPointInside(self, p):
43        hasPI = False
44        for component in self._components:
45            if component.hasPointInside(p):
46                hasPI = True
47                break
48
49        return hasPI
50
51    def intersectSegment(self, a, b, minS=None, maxS=None, intersectionMargin=0.):
52        intersect = (False,np.array([]))
53        for component in self._components:
54            current = component.intersectSegment(a,b,minS,maxS,intersectionMargin)
55            if current[0]:
56                intersect = current
57                break
58
59        return intersect
60
61    def intersectPolyhedron(self, polyhedron):
62        intersect = False
63        for component in self._components:
64            if component.intersectPolyhedron(polyhedron):

```

```

65         intersect = True
66         break
67
68     return intersect
69
70     def intersectPathTriple(self, triple):
71         intersect = (False, np.array([]))
72         for component in self._components:
73             current = component.intersectPathTriple(triple)
74             if current[0]:
75                 intersect = current
76                 break
77
78     return intersect
79
80     def plotAllPoints(self, plotter):
81         for component in self._components:
82             component.plotAllPoints(plotter)
83
84     def plot(self, plotter):
85         for component in self._components:
86             component.plot(plotter)
87
88     def extractXmlTree(self, root):
89         for component in self._components:
90             component.extractXmlTree(root)

```

### A.1.7 *tetrahedron.py*

```

1 import numpy as np
2 import polyhedron
3
4 class Tetrahedron(polyhedron.Polyhedron):
5     def __init__(self, a, b, c, d, invisible=False, distributePoints=True, maxEmptyArea=0.1):
6         super(Tetrahedron, self).__init__(np.array([[a,b,c],[a,b,d],[b,c,d],[c,a,d]]), invisible, distributePoints,
7                                         maxEmptyArea)
8
9     self._vertexes = [a,b,c,d]
10
11    def plot(self, plotter):
12        if self._invisible == False:
13            plotter.addTetrahedron(self._vertexes, plotter.COLOR_OBSTACLE)

```

### A.1.8 *parallelepiped.py*

```

1 import numpy as np
2 import polyhedron
3
4 class Parallelepiped(polyhedron.Polyhedron):
5     def __init__(self, a, b, invisible=False, distributePoints=True, maxEmptyArea=0.1, boundingBox=False):
6
7         c = [a[0], b[1], a[2]]
8         d = [b[0], a[1], a[2]]
9         e = [a[0], a[1], b[2]]
10        f = [b[0], b[1], a[2]]
11        g = [b[0], a[1], b[2]]
12        h = [a[0], b[1], b[2]]
13
14        super(Parallelepiped, self).__init__(faces=np.array([
15            [a,g,e],[a,d,g],[d,f,g],[f,b,g],[f,b,h],[f,h,c],
16            [h,a,e],[h,c,a],[e,h,g],[h,b,g],[a,d,f],[a,f,c]
17        ]), invisible=invisible, distributePoints=distributePoints, maxEmptyArea=maxEmptyArea, boundingBox=boundingBox)

```

### A.1.9 *convexHull.py*

```

1 import numpy as np
2 import scipy as sp
3 import scipy.spatial
4 import polyhedron
5
6 class ConvexHull(polyhedron.Polyhedron):
7     def __init__(self, points, invisible=False, distributePoints=True, maxEmptyArea=0.1):
8         convHull = sp.spatial.ConvexHull(points)
9         faces = []
10        for simplex in convHull.simplices:
11            faces.append([convHull.points[simplex[0]], convHull.points[simplex[1]], convHull.points[simplex[2]]])
12
13    super(ConvexHull, self).__init__(np.array(faces), invisible, distributePoints, maxEmptyArea)

```

### A.1.10 *bucket.py*

```

1 import numpy as np
2 import compositePolyhedron
3 import parallelepiped
4
5 class Bucket(compositePolyhedron.CompositePolyhedron):
6     def __init__(self, center, width, height, thickness, invisible=False, distributePoints=True, maxEmptyArea=0.1,
7                  ↪ boundingBox=False):
8         c = center
9         l = width
10        h = height
11        d = thickness
12        parallelepipeds = []
13
14        parallelepipeds.append(parallelepiped.Parallelepiped(
15            np.array([c[0]-(l/2), c[1]-(l/2), c[2]-(h/2)]), \
16            np.array([c[0]+(l/2), c[1]+(l/2), c[2]-(h/2)+d]), invisible, distributePoints, maxEmptyArea, boundingBox))
17
18        parallelepipeds.append(parallelepiped.Parallelepiped(
19            np.array([c[0]-(l/2), c[1]+(l/2)-d, c[2]-(h/2)+d]), \
20            np.array([c[0]+(l/2), c[1]+(l/2), c[2]+(h/2)]), invisible, distributePoints, maxEmptyArea, boundingBox))
21
22        parallelepipeds.append(parallelepiped.Parallelepiped(
23            np.array([c[0]-(l/2), c[1]-(l/2), c[2]-(h/2)+d]), \
24            np.array([c[0]+(l/2), c[1]-(l/2)+d, c[2]+(h/2)]), invisible, distributePoints, maxEmptyArea, boundingBox))
25
26        parallelepipeds.append(parallelepiped.Parallelepiped(
27            np.array([c[0]-(l/2), c[1]-(l/2)+d, c[2]-(h/2)+d]), \
28            np.array([c[0]+(l/2)+d, c[1]+(l/2)-d, c[2]+(h/2)]), invisible, distributePoints, maxEmptyArea, boundingBox))
29
30        parallelepipeds.append(parallelepiped.Parallelepiped(
31            np.array([c[0]+(l/2)-d, c[1]-(l/2)+d, c[2]-(h/2)+d]), \
32            np.array([c[0]+(l/2), c[1]+(l/2)-d, c[2]+(h/2)]), invisible, distributePoints, maxEmptyArea, boundingBox))
33
34    super(Bucket, self).__init__(parallelepipeds)

```

## A.2 SCRIPTS

### A.2.1 *makeRandomScene.py*

```

1 #!/bin/python
2
3 import sys
4 import numpy as np
5 import random
6 import math
7 import pickle
8 import voronizer
9 import tetrahedron
10
11 if len(sys.argv) >= 14 and len(sys.argv) <= 15:
12     i = 1

```

```

13     minX = float(sys.argv[i])
14     i += 1
15     minY = float(sys.argv[i])
16     i += 1
17     minZ = float(sys.argv[i])
18     i += 1
19     maxX = float(sys.argv[i])
20     i += 1
21     maxY = float(sys.argv[i])
22     i += 1
23     maxZ = float(sys.argv[i])
24     i += 1
25     bbMargin = float(sys.argv[i])
26     i += 1
27     fixedRadius = bool(eval(sys.argv[i]))
28     i += 1
29     if fixedRadius:
30         radius = float(sys.argv[i])
31         i += 1
32     else:
33         minRadius = float(sys.argv[i])
34         i += 1
35         maxRadius = float(sys.argv[i])
36         i += 1
37     avoidCollisions = bool(eval(sys.argv[i]))
38     i += 1
39     numObstacles = int(sys.argv[i])
40     i += 1
41     maxEmptyArea = float(sys.argv[i])
42     i += 1
43     fileName = sys.argv[i]
44
45 else:
46     minX = float(input('Insert min scene X: '))
47     minY = float(input('Insert min scene Y: '))
48     minZ = float(input('Insert min scene Z: '))
49     maxX = float(input('Insert max scene X: '))
50     maxY = float(input('Insert max scene Y: '))
51     maxZ = float(input('Insert max scene Z: '))
52     bbMargin = float(input('Insert bounding box margin: '))
53     fixedRadius = bool(eval(input('Do you want fixed obstacle radius? (True/False): ')))
54     if fixedRadius:
55         radius = float(input('Insert obstacle radius: '))
56     else:
57         minRadius = float(input('Insert min obstacle radius: '))
58         maxRadius = float(input('Insert max obstacle radius: '))
59     avoidCollisions = bool(eval(input('Do you want to avoid collisions between obstacles? (True/False): ')))
60     numObstacles = int(input('Insert obstacles number: '))
61     maxEmptyArea = float(input('Insert max empty area (for points distribution in obstacles): '))
62
63     fileName = input('Insert file name: ')
64
65 voronoi = voronizer.Voronizer()
66 obstacles = []
67
68 for ob in range(numObstacles):
69     print('Creating obstacle {} '.format(ob+1), end='', flush=True)
70     ok = False
71     while not ok:
72         print('.', end='', flush=True)
73         if not fixedRadius:
74             radius = random.uniform(minRadius,maxRadius)
75             center = np.array([random.uniform(minX+radius,maxX-radius), random.uniform(minY+radius,maxY-radius), random.uniform(
76                 ↪ minZ+radius,maxZ-radius)])
77             points = []
78             for pt in range(4):
79                 elev = random.uniform(-math.pi/2., math.pi/2.)
80                 azim = random.uniform(0., 2.*math.pi)
81                 points[:0] = [center+np.array([
82                     radius*math.cos(elev)*math.cos(azim),
83                     radius*math.cos(elev)*math.sin(azim),
84                     radius*math.sin(elev)])]
85
85             newObstacle = tetrahedron.Tetrahedron(a = points[0], b = points[1], c = points[2], d = points[3], distributePoints =
86             ↪ True, maxEmptyArea = maxEmptyArea)
87
88             ok = True
89             if avoidCollisions:
90                 for obstacle in obstacles:
91                     if newObstacle.intersectPolyhedron(obstacle):
92                         ok = False
93                         break

```

```

93     if ok:
94         voronoi.addPolyhedron(newObstacle)
95         if avoidCollisions:
96             obstacles[:0] = [newObstacle]
97
98     print(' done', flush=True)
99
100 voronoi.addBoundingBox([minX-bbMargin, minY-bbMargin, minZ-bbMargin], [maxX+bbMargin, maxY+bbMargin, maxZ+bbMargin],
101                         ↪ maxEmptyArea, verbose=True)
102
103 voronoi.setPolyhedronsSites(verbose=True)
104 voronoi.makeVoroGraph(verbose=True)
105
106 print('Write file', flush=True)
107 record = {}
108 record['voronoi'] = voronoi
109
110 with open(fileName, 'wb') as f:
111     pickle.dump(record, f)

```

### A.2.2 makeBucketScene.py

```

1  #!/bin/python
2
3  import sys
4  import numpy as np
5  import random
6  import math
7  import pickle
8  import voronizer
9  import bucket
10
11 if len(sys.argv) == 9:
12     i = 1
13     minPoint = np.array(tuple(eval(sys.argv[i])), dtype=float)
14     i += 1
15     maxPoint = np.array(tuple(eval(sys.argv[i])), dtype=float)
16     i += 1
17     center = np.array(tuple(eval(sys.argv[i])), dtype=float)
18     i += 1
19     width = float(sys.argv[i])
20     i += 1
21     height = float(sys.argv[i])
22     i += 1
23     thickness = float(sys.argv[i])
24     i += 1
25     maxEmptyArea = float(sys.argv[i])
26     i += 1
27     fileName = sys.argv[i]
28
29 else:
30     minPoint = np.array(tuple(eval(input('Insert min point (x,y,z): '))), dtype=float)
31     maxPoint = np.array(tuple(eval(input('Insert max point (x,y,z): '))), dtype=float)
32     center = np.array(tuple(eval(input('Insert bucket center point (x,y,z): '))), dtype=float)
33     width = float(input('Insert bucket width: '))
34     height = float(input('Insert bucket height: '))
35     thickness = float(input('Insert bucket thickness: '))
36     maxEmptyArea = float(input('Insert max empty area (for points distribution in obstacles): '))
37     fileName = input('Insert file name: ')
38
39 voronoi = voronizer.Voronizer()
40
41 print('Create bucket', flush=True)
42 voronoi.addPolyhedron(bucket.Bucket(center, width, height, thickness, distributePoints=True, maxEmptyArea=maxEmptyArea))
43 voronoi.addBoundingBox(minPoint, maxPoint, maxEmptyArea, verbose=True)
44 voronoi.setPolyhedronsSites(verbose=True)
45 voronoi.makeVoroGraph(verbose=True)
46
47 print('Write file', flush=True)
48 record = {}
49 record['voronoi'] = voronoi
50
51 with open(fileName, 'wb') as f:
52     pickle.dump(record, f)

```

### A.2.3 *plotScene.py*

```

1 #!/bin/python
2
3 import sys
4 import pickle
5 import plotter
6
7 if len(sys.argv) >= 2:
8     if len(sys.argv) == 4:
9         i = 2
10        plotSites = bool(eval(sys.argv[i]))
11        i += 1
12        plotGraph = bool(eval(sys.argv[i]))
13    else:
14        plotSites = bool(eval(input('Do you want to plot Voronoi sites? (True/False): ')))
15        plotGraph = bool(eval(input('Do you want to plot graph? (True/False): ')))
16
17    print('Load file', flush=True)
18    with open(sys.argv[1], 'rb') as f:
19        record = pickle.load(f)
20
21    voronoi = record['voronoi']
22
23    print('Build renderer, window and interactor', flush=True)
24    plt = plotter.Plotter()
25
26    voronoi.plotPolyhedrons(plt, verbose = True)
27    if plotSites:
28        voronoi.plotSites(plt, verbose = True)
29    if plotGraph:
30        voronoi.plotGraph(plt, verbose = True)
31
32    print('Render', flush=True)
33    plt.draw()
34
35 else:
36     print('use: {} sceneFile [plotSites plotGraph]'.format(sys.argv[0]))
37

```

### A.2.4 *executeInScene.py*

```

1 #!/bin/python
2
3 import sys
4 import numpy as np
5 import pickle
6 import plotter
7
8 if len(sys.argv) >= 2:
9     if len(sys.argv) == 8:
10         i = 2
11         startPoint = np.array(tuple(eval(sys.argv[i])),dtype=float)
12         i += 1
13         endPoint = np.array(tuple(eval(sys.argv[i])),dtype=float)
14         i += 1
15         bsplineDegree = int(sys.argv[i])
16         i += 1
17         useMethod = str(sys.argv[i])
18         i += 1
19         postSimplify = bool(eval(sys.argv[i]))
20         i += 1
21         adaptivePartition = bool(eval(sys.argv[i]))
22     else:
23         startPoint = np.array(tuple(eval(input('Insert start point (x,y,z): '))),dtype=float)
24         endPoint = np.array(tuple(eval(input('Insert end point (x,y,z): '))),dtype=float)
25         bsplineDegree = int(input('Insert B-spline degree (2/3/4): '))
26         useMethod = str(input('Which method you want to use? (none/trijkstra/cleanPath/annealing): '))
27         postSimplify = bool(eval(input('Do you want post processing? (True/False): ')))
28         adaptivePartition = bool(eval(input('Do you want adaptive partition? (True/False): ')))
29
30     print('Load file', flush=True)
31     with open(sys.argv[1], 'rb') as f:
32         record = pickle.load(f)

```

```

33 voronoi = record['voronoi']
34 voronoi.setBsplineDegree(bsplineDegree)
35 voronoi.setAdaptivePartition(adaptivePartition)
36
37 voronoi.calculateShortestPath(startPoint, endPoint, 'near', useMethod=useMethod, postSimplify=postSimplify, verbose=True,
38     ↪ debug=False)
39
40 print('Build renderer, window and interactor', flush=True)
41 plt = plotter.Plotter()
42
43 #voronoi.plotSites(plt, verbose = True)
44 voronoi.plotPolyhedrons(plt, verbose = True)
45 #voronoi.plotGraph(plt, verbose = True)
46 voronoi.plotShortestPath=plt, verbose = True)
47
48 print('Render', flush=True)
49 plt.draw()
50
51 else:
52     print('use: {} sceneFile [startPoint endPoint degree(2,4) useMethod postProcessing adaptivePartition]'.format(sys.argv
53         ↪ [0]))

```

### A.2.5 *scene2coord.py*

```

1 #!/bin/python
2
3 import sys
4 import pickle
5 import xml.etree.cElementTree as ET
6
7 if len(sys.argv) == 3:
8
9     print('Load file', flush=True)
10    with open(sys.argv[1], 'rb') as f:
11        record = pickle.load(f)
12
13    voronoi = record['voronoi']
14
15    print('Create XML', flush=True)
16    xmlRoot = ET.Element('scene')
17    voronoi.extractXmlTree(xmlRoot)
18    xmlTree = ET.ElementTree(xmlRoot)
19
20    print('Write file', flush=True)
21    xmlTree.write(sys.argv[2])
22
23 else:
24     print('use: {} sceneFile coordinateFile'.format(sys.argv[0]))

```

### A.2.6 *coord2scene.py*

```

1 #!/bin/python
2
3 import sys
4 import pickle
5 import xml.etree.cElementTree as ET
6 import voronizer
7
8 if len(sys.argv) == 4:
9     xmlFileName = sys.argv[1]
10    sceneFileName = sys.argv[2]
11    maxEmptyArea = float(sys.argv[3])
12
13    xmlRoot = ET.parse(xmlFileName).getroot()
14
15    voronoi = voronizer.Voronizer()
16
17    print('Import XML', flush=True)
18    voronoi.importXmlTree(xmlRoot, maxEmptyArea)

```

```
19     print('Set sites and make graph', flush=True)
20     voronoi.setPolyhedronsSites(verbose=True)
21     voronoi.makeVoroGraph(verbose=True)
22
23     print('Write file', flush=True)
24     record = {}
25     record['voronoi'] = voronoi
26     with open(sceneFileName, 'wb') as f:
27         pickle.dump(record, f)
28
29 else:
30     print('use: {} coordinateFile sceneFile maxEmptyArea'.format(sys.argv[0]))
```

---

## BIBLIOGRAPHY

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## ACRONYMS

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- CAD** Computer-Aided Design  
**CAGD** Computer-Aided Geometric Design  
**CAM** Computer-Aided Manufacturing  
**CHP** Convex Hull Property  
**LR** Lagrangian Relaxation  
**MCM** Monte Carlo Method  
**OOP** Object Oriented Programming  
**OTF** Obstacle Triangular Face  
**PCLT** Probability central limit theorem  
**PDF** Probability Density Function  
**PE** Probable Error  
**PH** Pythagorean Hodograph  
**RRT** Rapidly-expanding Random Tree  
**SA** Simulated Annealing  
**UAV** Unmanned Aerial Vehicle  
**UML** Unified Modeling Language  
**VD** Voronoi Diagram  
**VTK** Visualization Tool Kit  
**XML** eXtensible Markup Language



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