Volume Parameterization for Multi-block Meshes

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07/19/2017
WPAFB HPC Internship Program Presentation Session

Introduction

- Cameron Mackintosh
- Dayton, Ohio
- Carnegie Mellon University, class of 2019
- Electrical and Computer Engineering Undergraduate
- C programming, amateur radio, foreign languages

Project

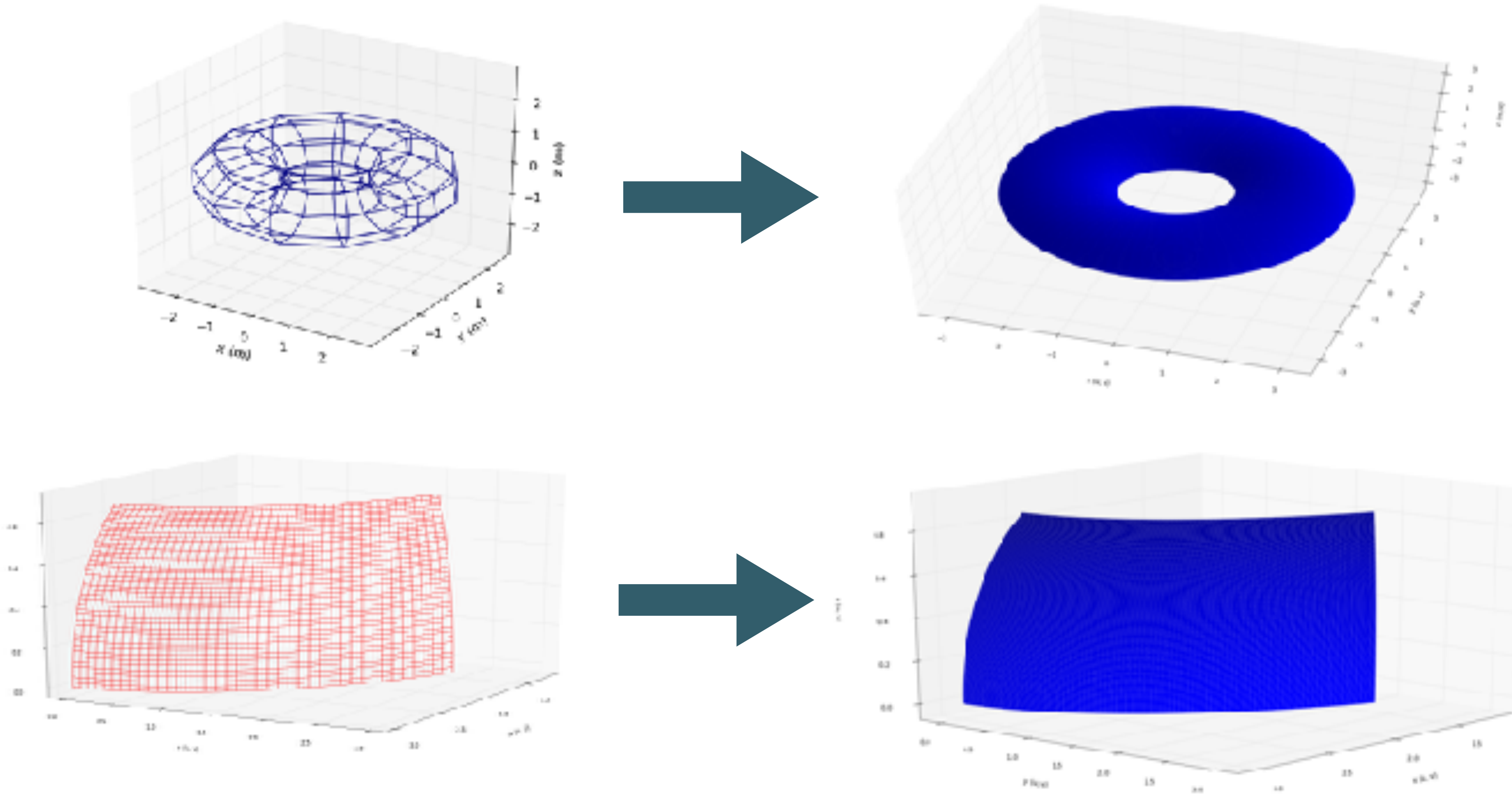
- AFRL Ablation Fluid Structure Interaction (AFSI)
  - Develop volume parameterization code for multi-block meshes suitable for hypersonic simulations and integrate it with AFSI.
  - Initial work performed under PETTT KY07 Internship Program.
- Wright Patterson Air Force Base DSRC
- Mentor: Konstantinos Vogiatzis (HPCMP PETTT/Engility)
- Customer: Ryan Gosse (AFRL/RQHF)

Task Agreement

- Learn AFSI data types, Git, object-oriented Fortran.
- Interface code with AFSI.
- Reduce arc length parameterization error.
- Automate selection of parameter space clustering.
- Add De Casteljau algorithm.
- Interface multi-block structured meshes at block boundaries.
- Test with mesh deformation.

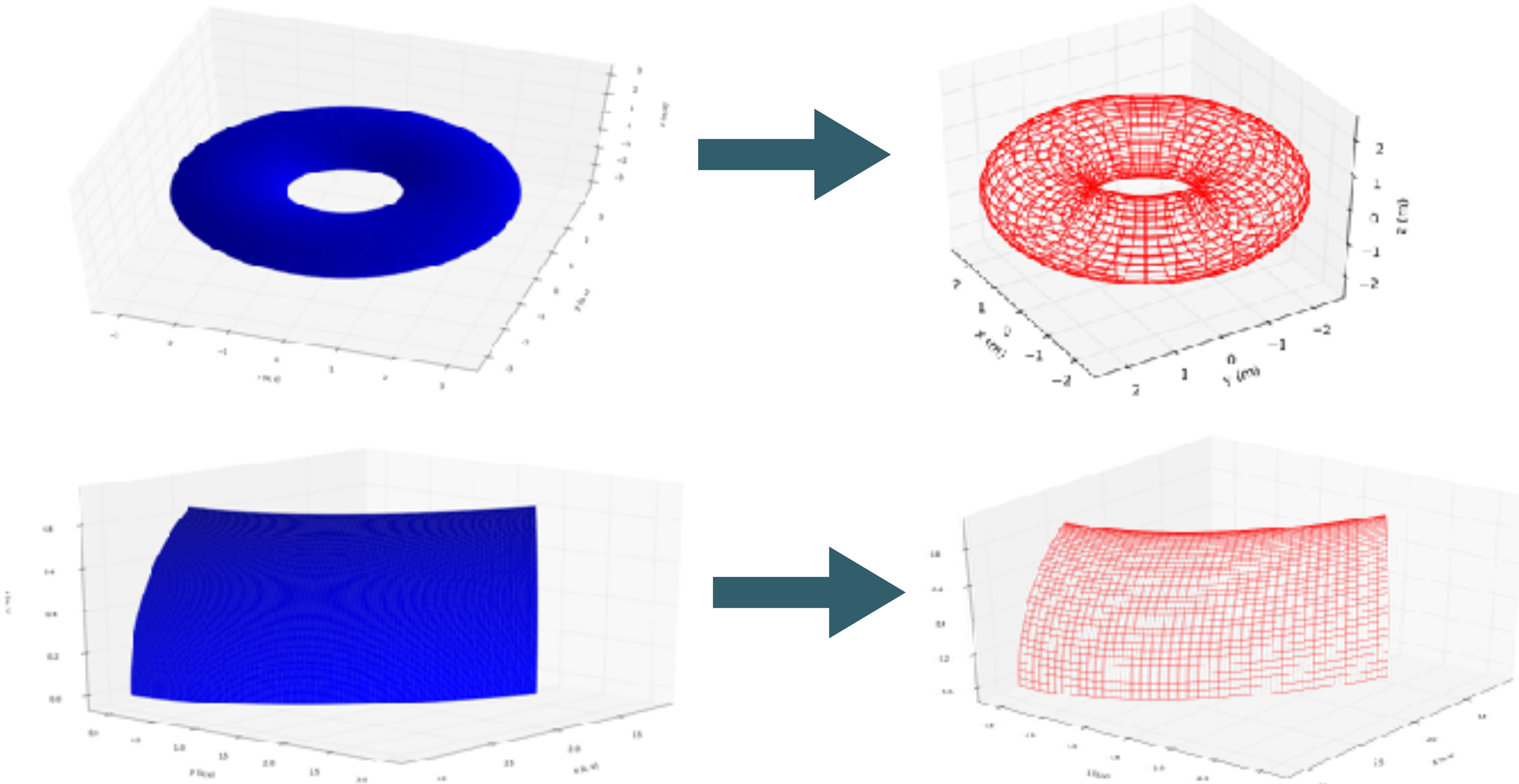
Mesh Parameterization

- Mesh parameterization:



Mesh Parameterization

- Mesh refinement:



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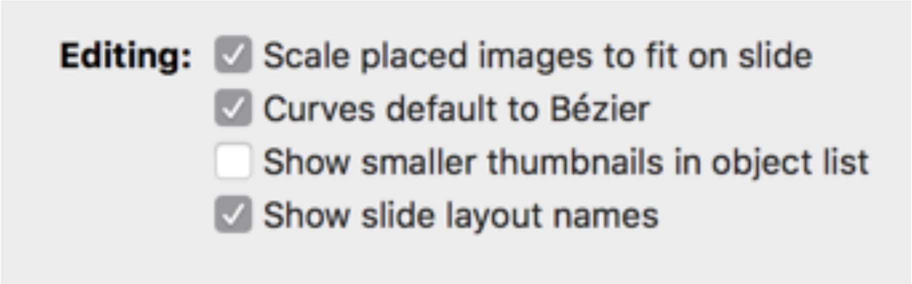
Proposed Approach

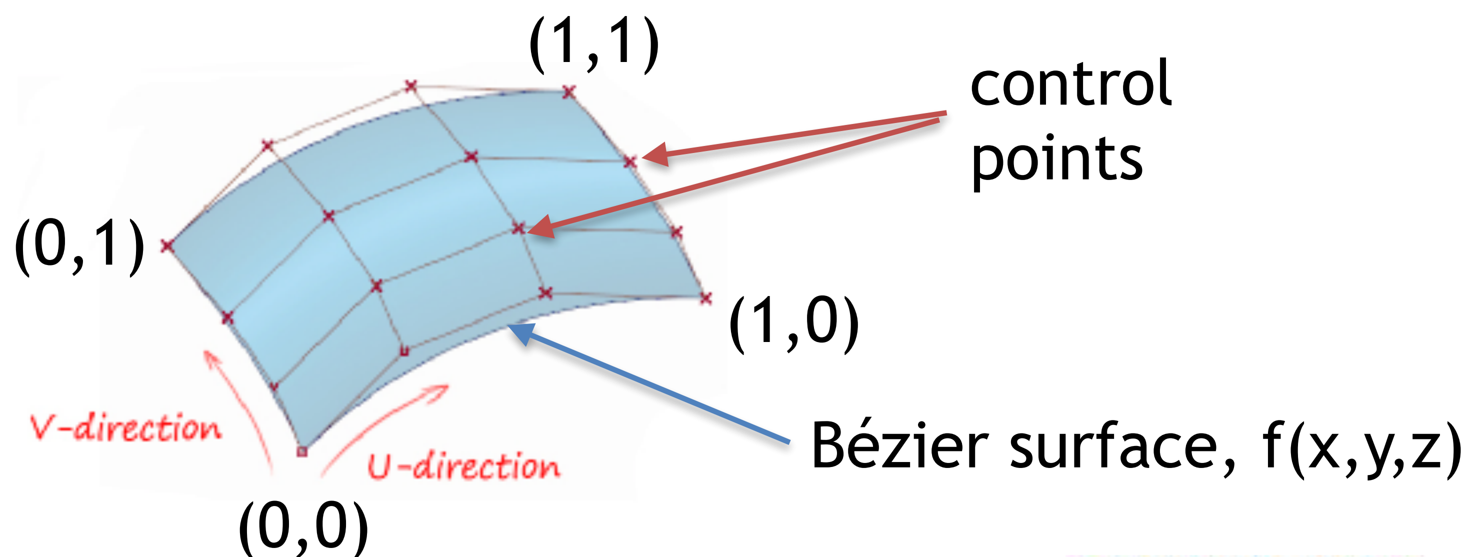
- Bézier parametric definition of a curve is common in computer geometry, from this presentation software to video games



- Extending the Bézier curves to surfaces and volumes, it now suites structured mesh parameterization.

Proposed Approach

- Consider surfaces from here on, for explanation's sake.
- What is a Bézier surface?
  - A Bézier surface is a parametric surface defined by a grid of control points.
  - Points on a Bézier surface are represented by their u and v parameters, both ranging from 0 to 1.



Proposed Approach

- Calculating points on a Bézier surface:
  - A point's xyz values can be calculated from the point's uv values and the Bézier surface's control points.
  - This is done either by applying the Bézier equation or by applying the faster De Casteljau algorithm.

Proposed Approach

- Bézier equation:

$$Bez_x(u,v) = \sum_{i=1}^{n_u+1} \sum_{j=1}^{n_v+1} \left(\left[\binom{n_u}{i} \cdot u^i \cdot (1-u)^{n_u - i} \right] \cdot \left[\binom{n_v}{j} \cdot v^j \cdot (1-v)^{n_v - j} \right] \cdot \mathbf{x}_{i,j} \right)$$

n_u : u order

n_v: v order

$n_{\mathrm{cpu}} = n_u + 1$: number of control points in u direction

$n_{\mathrm{cpv}} = n_v + 1$: number of control points in v direction

$\mathbf{x}$: $n_{\mathrm{cpu}} \times n_{\mathrm{cpv}}$ matrix of x control points

u : u value of point to calculate xyz value of

v : v value of point to calculate xyz value of

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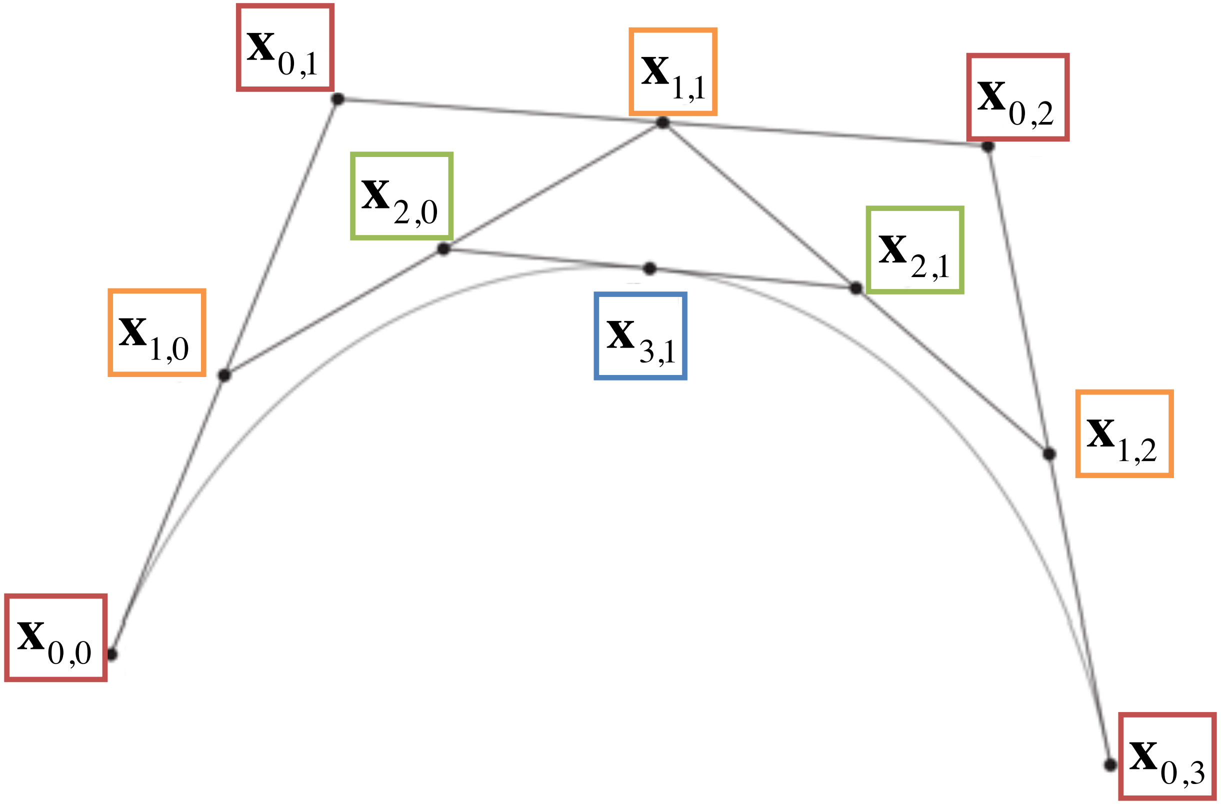
Proposed Approach

- De Casteljau algorithm for curves:

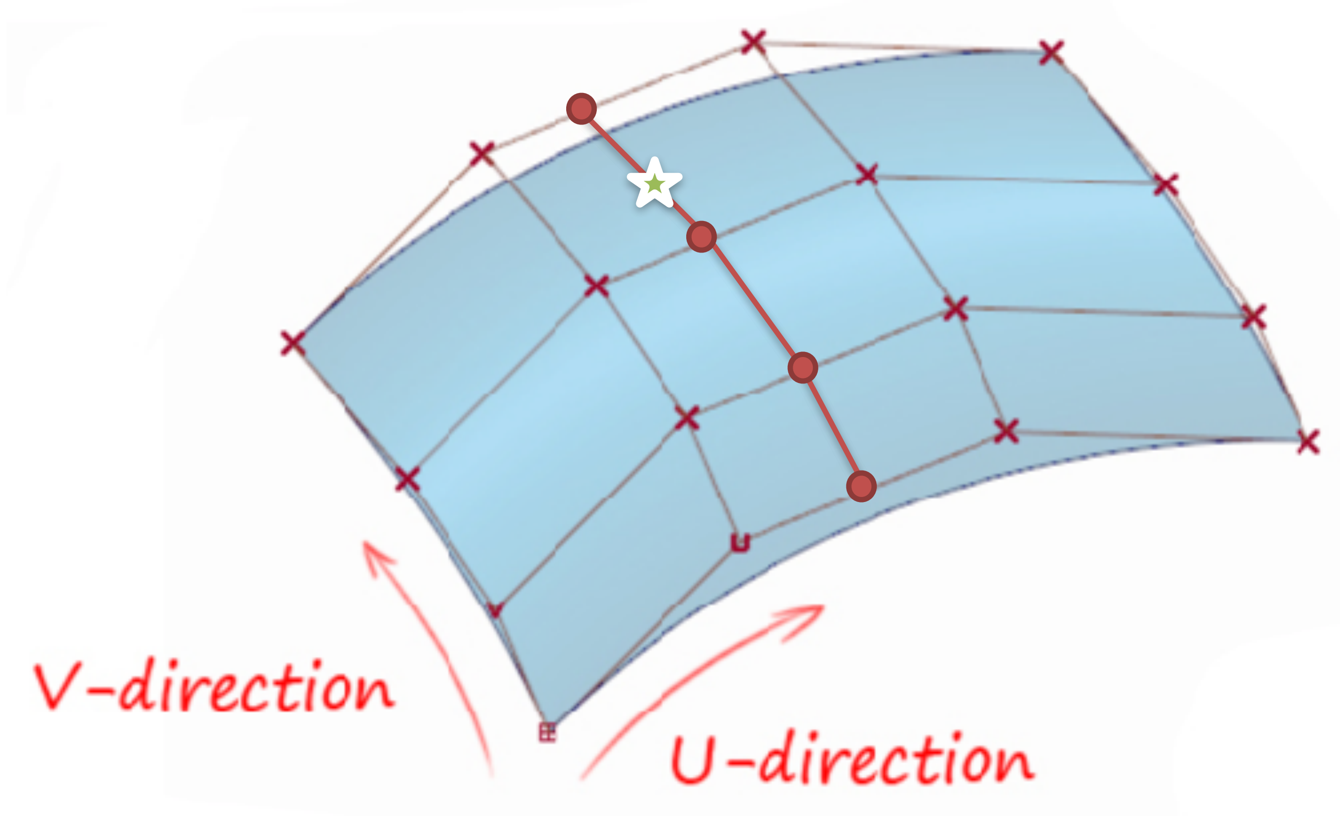
$$\mathbf{x}_{i,j} = (1-u)\mathbf{x}_{i-1,j} + u\mathbf{x}_{i-1,j-1}$$



Proposed Approach

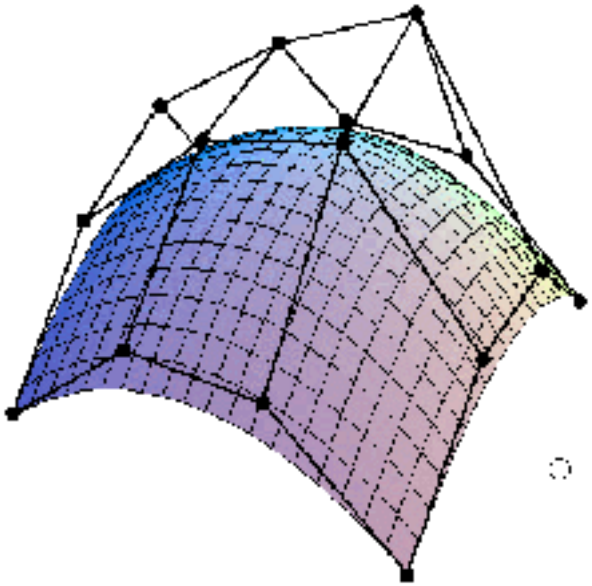
- De Casteljau algorithm for surfaces:

$$(u = 0.5, v = 0.8)$$



Proposed Approach

- How do Bézier surfaces relate to structured mesh parameterization and refinement?
  - A Bézier surface can be fitted to an initial mesh.
  - The initial meshes' points are each assigned uv parameter values. This process is called parameterization.
  - The Bézier equation in matrix form is solved for control points by least squares approximation, as the equation is overdetermined.



  - A new structured mesh can be generated on any uv value distribution using the calculated control points.

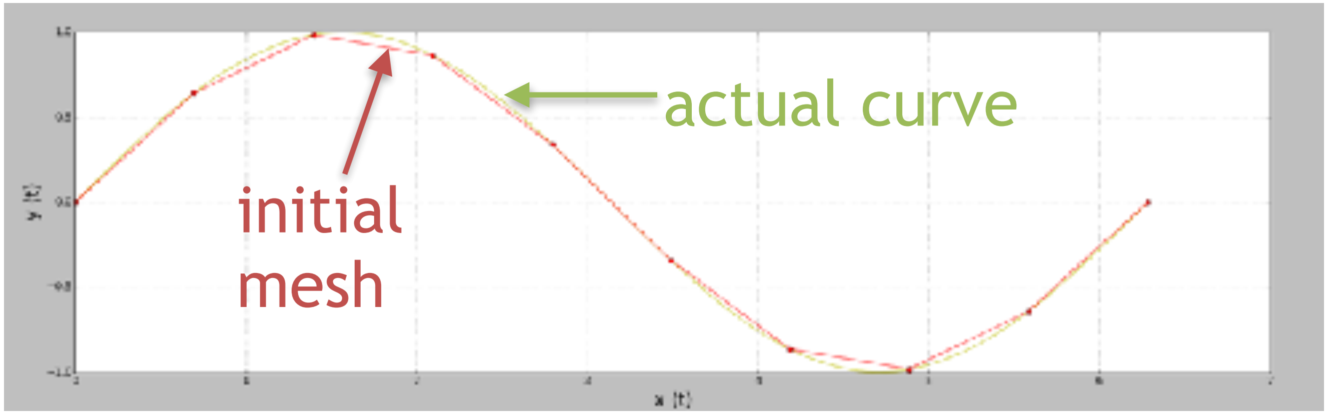
$$\mathbf{B}_{n_{\mathrm{in}} \times n_{\mathrm{cp}}} \times \mathbf{x}_{\mathrm{cp}} = \mathbf{x}_{\mathrm{in}} \qquad \mathbf{B}_{n_{\mathrm{new}} \times n_{\mathrm{cp}}} \times \mathbf{x}_{\mathrm{cp}} = \mathbf{x}_{\mathrm{new}}$$

$$\mathbf{B}_{n_{\mathrm{in}} \times n_{\mathrm{cp}}} \times \mathbf{y}_{\mathrm{cp}} = \mathbf{y}_{\mathrm{in}} \qquad \mathbf{B}_{n_{\mathrm{new}} \times n_{\mathrm{cp}}} \times \mathbf{y}_{\mathrm{cp}} = \mathbf{y}_{\mathrm{new}}$$

$$\mathbf{B}_{n_{\mathrm{in}} \times n_{\mathrm{cp}}} \times \mathbf{z}_{\mathrm{cp}} = \mathbf{z}_{\mathrm{in}} \qquad \mathbf{B}_{n_{\mathrm{new}} \times n_{\mathrm{cp}}} \times \mathbf{z}_{\mathrm{cp}} = \mathbf{z}_{\mathrm{new}}$$

Proposed Approach

- Arch length parameterization approximation problem:
  - An initial mesh is approximately parameterized by arc length.
  - A generated new mesh’s parameterization has a slight offset.
    - There’s a variation between arc lengths calculated from the coarse initial mesh and the fine new mesh.
  - The solution is to generate a table that maps uv values to skewed uv values to minimize this offset.
  - The size of the table can be reduced and a Bézier curve can be fit to this table to reduce the computational expense.



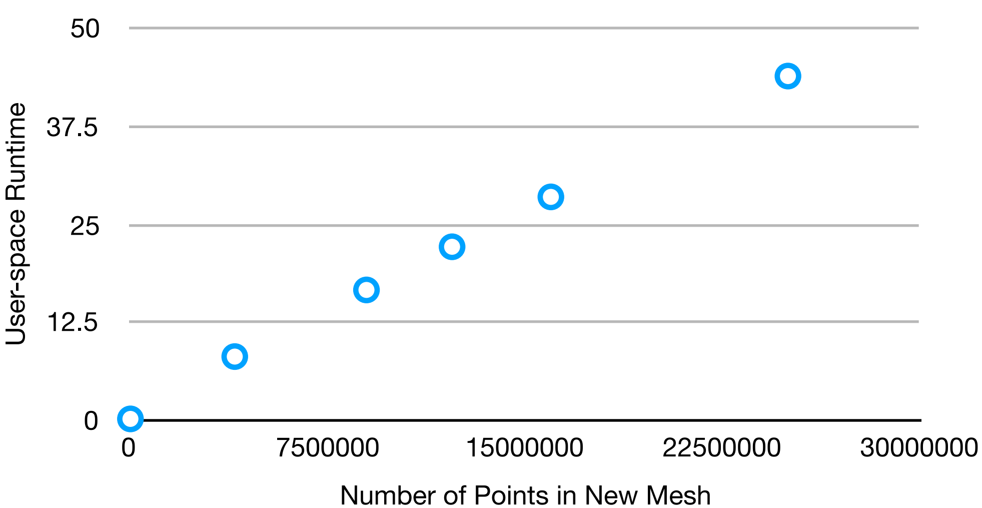
Proposed Approach

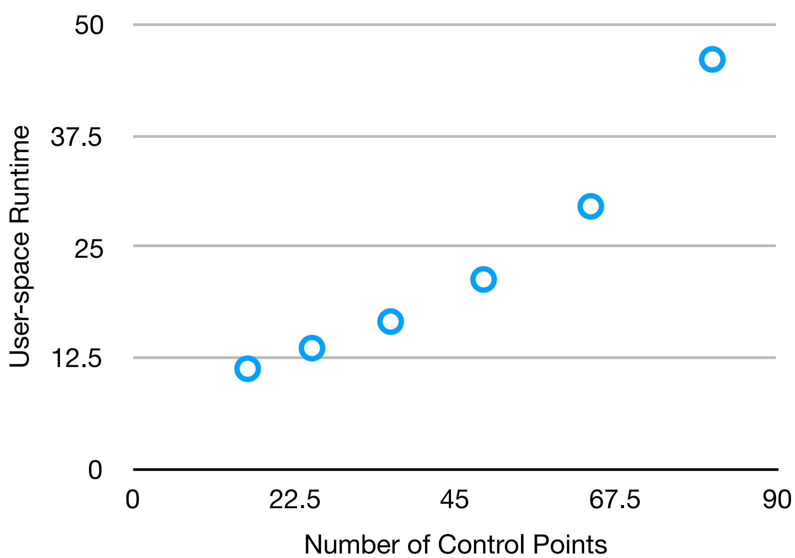
- Arch length parameterization approximation problem (cont.):
  - Initial mesh has 10 points. New meshes each have 20 points.
  - New meshes are generated from uniform uv distributions.

	Standard Deviation of Segment Lengths	Sum of Squared Residuals Square (Between Mesh and Actual Curve)
Without Arc Length Table	0.0270	0.000917
With Arc Length Table	0.00056	0.000914

Solution

- Fortran library was developed that implements a Bézier-based parameterization and refitting and is easily integrated into AFSI. The library implements all discussed methodologies.
- Serial performance:





Summary

- Benefits to HPCMP:
  - Applications requiring mesh deformation (e.g. ablation) or mesh refinement during simulation.
  - Multi-billion element structured meshes may be represented by control points, reducing memory and disk overhead.
- Current development:
  - Adding support for multi-block structured meshes.
  - Integrating with new AFSI types.

Lessons Learned

- How has the experience helped with my professional and personal growth?
  - Exposure to research and HPC community.
- How will I use this knowledge in my future studies?
  - Experience with development software (git, gdb, make, etc).
  - Experience with distributed development environment.
- How has the experience impacted my professional goals?
  - Found interest in computer aided geometric design.

Acknowledgment

This work was funded by the DoD High Performance Computing Modernization Program (HPCMP) through its User Productivity Enhancement, Technology Transfer and Training (PETTT) program. We would like to thank the DoD Supercomputing Resource Centers for making their computational resources available to us.