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Anatomical Mesh-Based Virtual Fixtures for Surgical Robots

IROS 2020, Las Vegas

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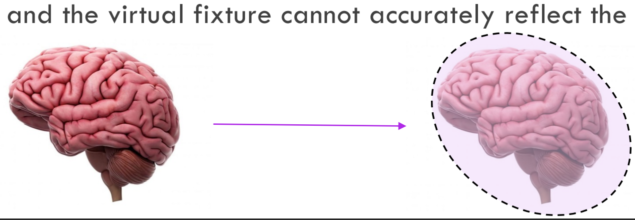
Challenges

Virtual fixture is often used for increased efficiency and operation safety.

However, it is challenging to automatically generate virtual fixture for complex anatomies.

Existing researches usually approximate the anatomical shape when using parametric forms such as ellipsoid [4][5][6], or using sparse level-set functions [7]. The process is labor intensive, and the virtual fixture cannot accurately reflect the anatomical shape.



Virtual fixture approximates the anatomy as an ellipsoid

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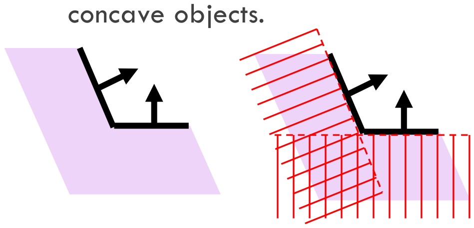
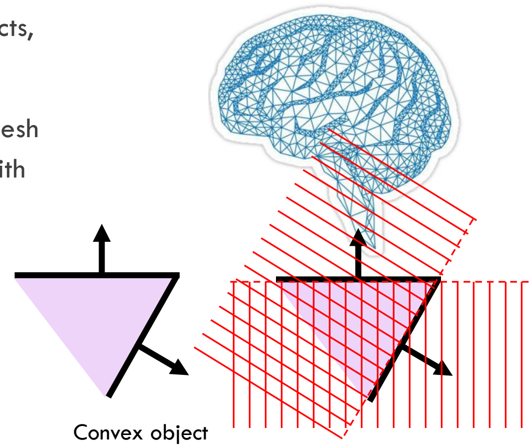
Challenges

Mesh is an intuitive representation of 3D objects, which is widely used in medical imaging.

Prior work [8] proposes to treat triangles in mesh as plane constraints. However, it only works with concave objects.



Concave object



Convex object

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Virtual Fixture Formulation

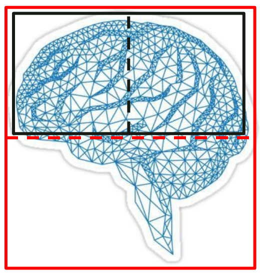
In this work, an anatomical mesh-based virtual fixture is proposed

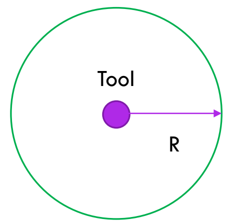
- Generates virtual fixture for complex anatomy automatically
- Implements an efficient and dynamic formulation

Virtual Fixture Formulation

Mesh-based constraint formulation algorithm is based on closest point (CP) and local geometry

- Store mesh as principle-direction tree (PD-Tree) [9] and define a motion sphere





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Virtual Fixture Formulation

Mesh-based constraint formulation algorithm is based on closest point (CP) and local geometry

- Store mesh as principle-direction tree (PD-Tree) [9] and define a motion sphere
- Determine the closest point on triangles

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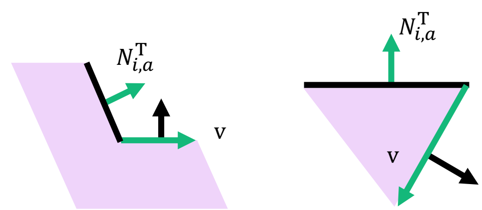
Virtual Fixture Formulation

Mesh-based constraint formulation algorithm is based on closest point (CP) and local geometry

- Store mesh as principle-direction tree (PD-Tree) [9] and define a motion sphere
- Determine the closest point on triangles
- Determine the local geometry

$$\text{geometry} = \begin{cases} \text{concave if } N_{i,a}^{\mathrm{T}}\mathrm{v} > 0 \\ \text{concex if } N_{i,a}^{T}\mathrm{v} < 0 \end{cases}$$



Concave object Convex object

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Virtual Fixture Formulation

Mesh-based constraint formulation algorithm is based on closest point (CP) and local geometry

Algorithm 1: Polygon Mesh Constraint

Input: PD-Tree, Current Position x
Result: List of Active Plane Constraints $\mathcal{L}$
Find intersected triangles $\mathcal{T}$, corresponding closest points $\mathcal{CP}$ and face normals $\mathcal{N}$;
for *triangle* $\mathcal{T}_i \in \mathcal{T}$ **do**
  if $\mathcal{CP}_i$ *in-triangle* & $\mathcal{N}_i^T(x - \mathcal{CP}_i) \geq 0$ **then**
    add $\{\mathcal{N}_i, \mathcal{CP}_i\}$ to $\mathcal{L}$;
  else if $\mathcal{CP}_i$ *on-edge* **then**
    Find adjacent triangle(s) $\mathcal{T}_{i,a}$;
    if $\mathcal{CP}_i == \mathcal{CP}_{i,a}$ & *locally convex* **then**
      add $\{x - \mathcal{CP}_i, \mathcal{CP}_i\}$ to $\mathcal{L}$;
    else if $\mathcal{N}_i^T(x - \mathcal{CP}_i) \geq 0$ & *locally concave* **then**
      add $\{\mathcal{N}_i, \mathcal{CP}_i\}$ to $\mathcal{L}$;
end

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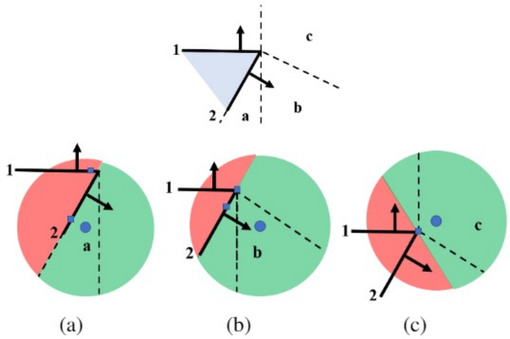
Virtual Fixture Formulation

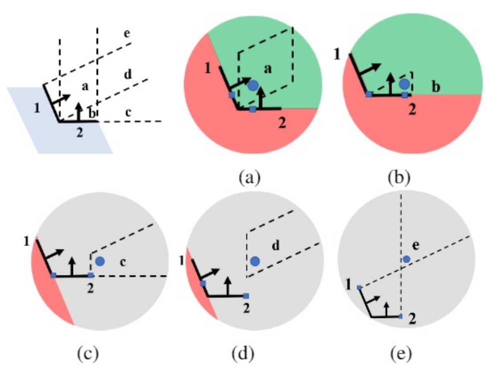
Mesh-based constraint formulation algorithm is based on closest point (CP) and local geometry



: tool position
: closest point
Green region: allowable
Red region: forbidden

Virtual Fixture Formulation

Mesh-based constraint formulation algorithm is based on closest point (CP) and local geometry



: tool position
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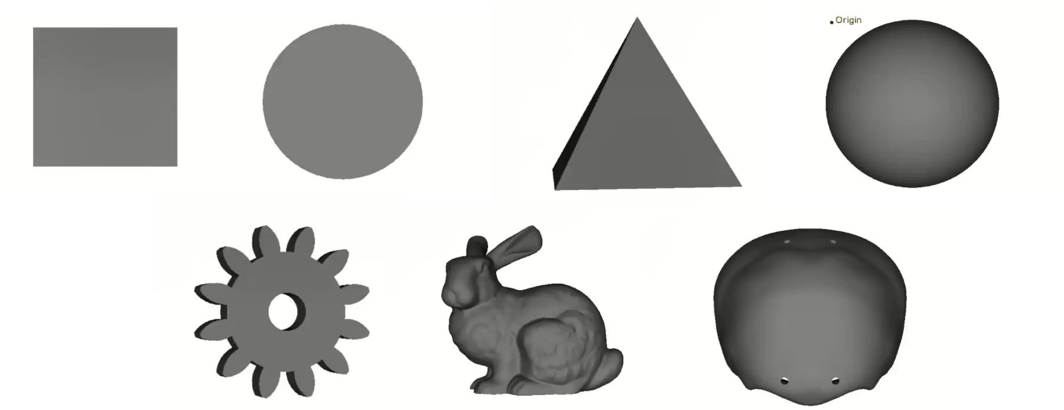
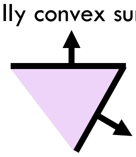
Evaluation - Simulation

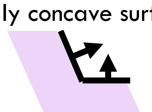


Evaluation - Simulation

2D illustration of locally convex surface.



2D illustration of locally concave surface.



Tool is outside the objects, thus facing locally **convex** surface (Fig 1);

Red: Tool position **without** virtual fixture
Blue: Tool position **with** virtual fixture

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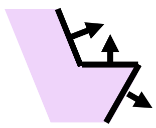
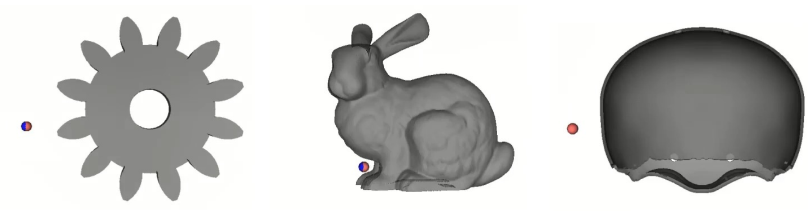
Evaluation - Simulation

2D illustration of locally concave and convex surface.



The following objects have both locally **concave and convex surfaces** (Fig 3).



Red: Tool position **without** virtual fixture
Blue: Tool position **with** virtual fixture

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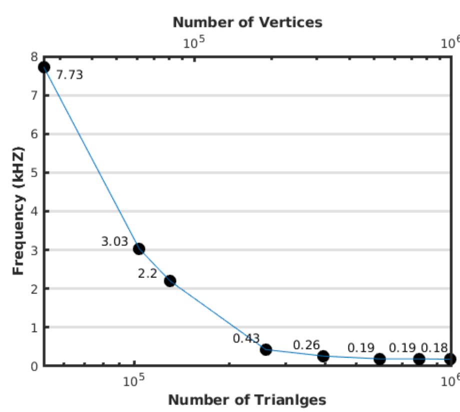
Evaluation – Runtime Analysis

Setup:
- Ubuntu 18.04
- Intel Core i7-8700



Evaluation – Skull Experiment

Craniosynostosis:

- fused cranial sutures do not allow for proper expansion of the skull as the child grows
- operation requires precise movement to avoid incision related complications [2]

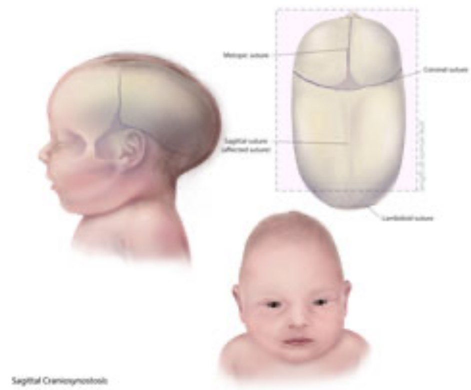
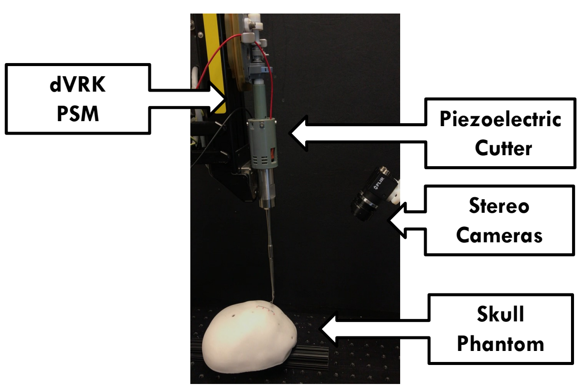


Fig 1. Craniosynostosis [source].

Evaluation – Skull Experiment



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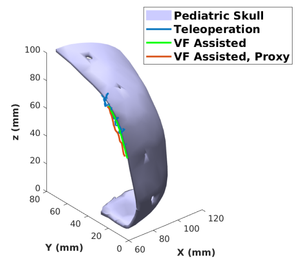
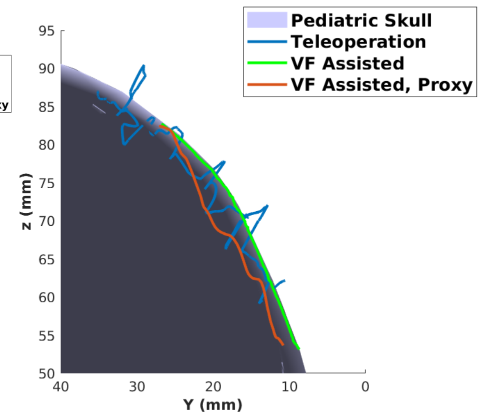
Evaluation – Skull Experiment

Experiment 1 - Skull tracing:

- Trace the planned path without cutting
- Evaluate the improvement of depth perception





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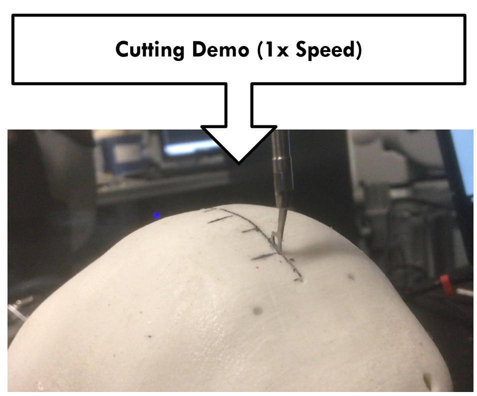
Evaluation – Skull Experiment

Experiment 2 - Skull cutting:

- Cut along the planned path
- Evaluate the improvement of penetration depth and path deviation



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Evaluation – Skull Experiment

Experiment 2 - Skull cutting:

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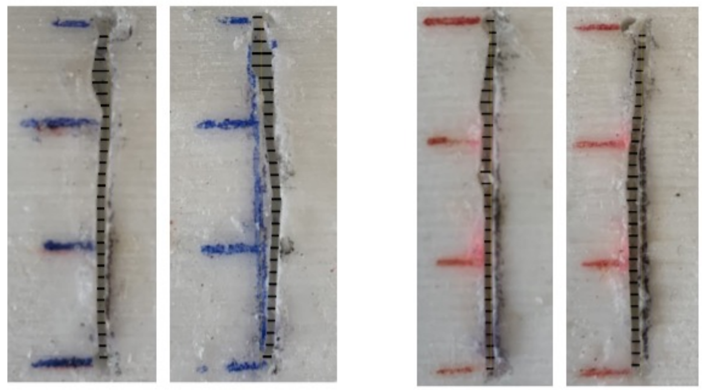

Teleop VF assisted

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Evaluation – Skull Experiment

Experiment 2 - Skull cutting:

- Cut along the planned path
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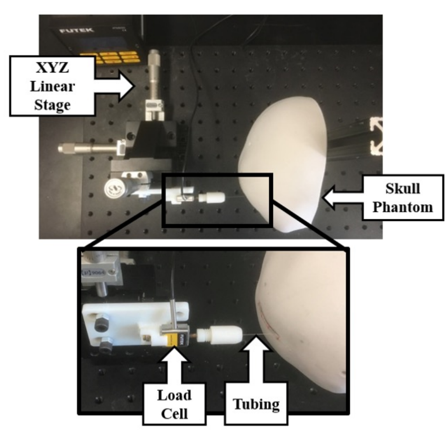

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Evaluation – Skull Experiment

Experiment 2 - Skull cutting:

- Cut along the planned path
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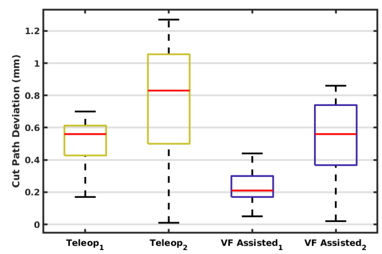

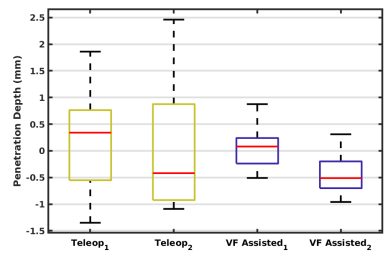

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Limitation and Future Work

Limitation:

- Position only
- Proof of concept experiment

Future work:

- 6-DoF virtual fixture
- Larger scale user studies

Acknowledgement

This work was supported:

- in part by a research contract from Galen Robotics,
- in part by Johns Hopkins University internal funds,
- and in part by Division of Plastic Surgery and Neurosurgery at Hospital for Sick Children.

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Contact

- The open-sourced implementation can be found at: github.com/mli0603/PolygonMeshVirtualFixture
- If you have any questions, you can reach me via email at: zli122@jhu.edu

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