Parness et al., 2013

# Advancing Microspine Gripper Modelling for Microgravity Climbing

Steven Morad
SpaceTREx, University of Arizona

# Outline

- Introduction
- Background
- Objective
- Method
- Conclusion
- Future Work
- Depending on time: Future Work - Scoring Grips

# Introduction – Microgravity Surface Mobility

- **What is microgravity surface mobility?**
  - **Moving about the surface of small bodies such as asteroids, comets, and artificial satellites**

# Introduction – Case for Microgravity Mobility

- Microgravity surface mobility opens the door to surface operations on small bodies
  - Small body science and analysis
  - Small body in-situ resource utilization
  - Satellite/ISS/spacecraft repair and servicing

Lucasfilms, 1999

# Background – Mobility Methods

- Mobility on microgravity bodies is difficult
- Wheels can’t get traction, reaction torque sends rovers into a tumble
- Hopping robots can inadvertently escape the body
  - Especially with nonuniform gravity
- Hovering requires corrections which use fuel over time, and in the case of asteroids blows regolith everywhere, obscuring cameras
- What about climbing?

# Background – Define Climbing

- We define climbing as an incremental process where part of the climber is always in contact with the body
  - Does not require fuel
  - Cannot escape body unless grip fails
  - Allows for momentum transfer to body
    - Can damp motion from reaction forces/torques generated moving around

# Background – Anchoring Methods

- How do we keep the climber in contact or "anchored" to the body?
    - Electroadhesion
    - Microspines

# Background - Electroadhesion

- Electroadhesive Pads
  - Run current through it, gets sticky
  - Requires constant power to maintain hold
  - Relatively weak adhesive force
    - 0.1-1 N/cm^2

Tweney/SRI, 2011

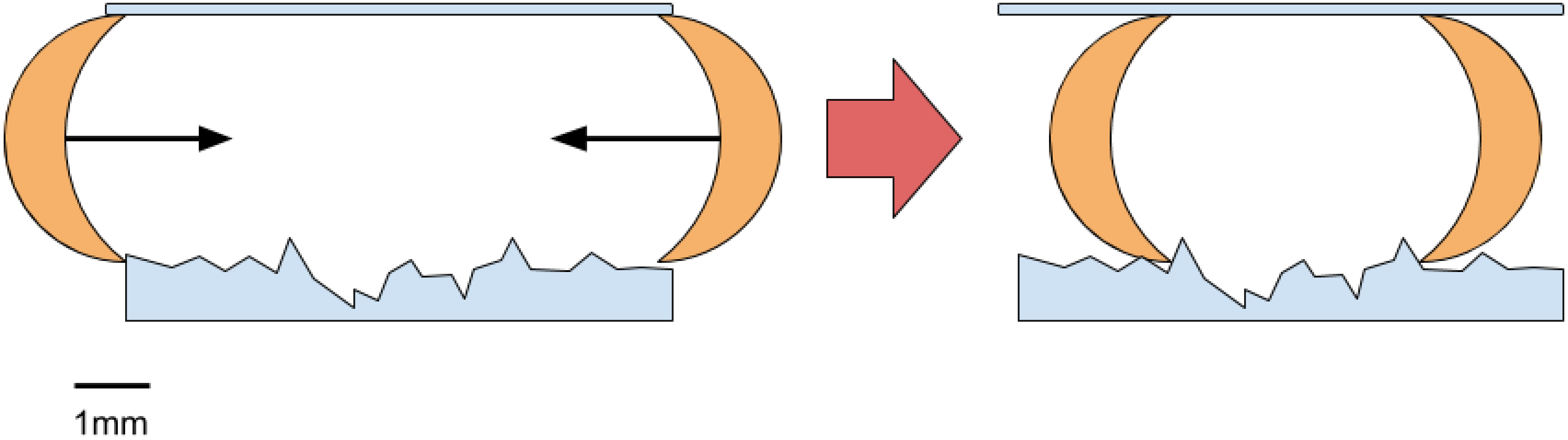
# Background - Microspines

- Microspines
  - No power required to maintain hold
  - Relatively strong adhesive force (1-2N per spine)
  - Does not work well on microscopically smooth surfaces
    - Rare in nature

Parness et al., 2017

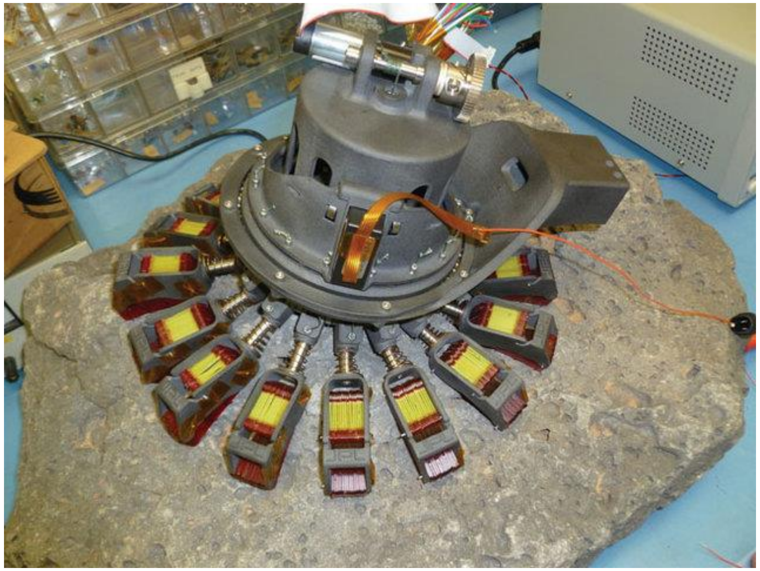
# Background – Microspine Mechanism

- Hooks/spines grip onto surface imperfections (asperities)
- Retracting the spines creates a grasp



# Background – Microspine Gripper

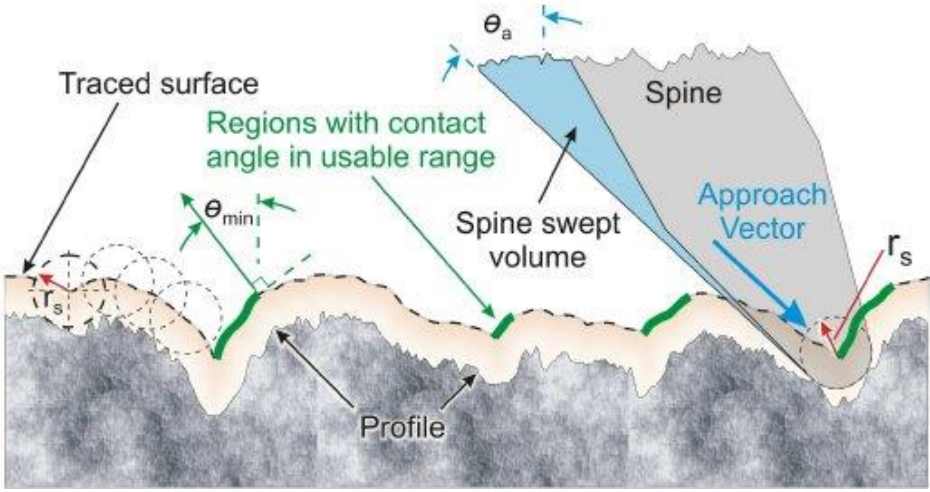
- Spines are arranged radially into grippers
  - Resists larger torques/forces in many directions



Parness et al., 2013

# Background – Theoretical Microspine Model

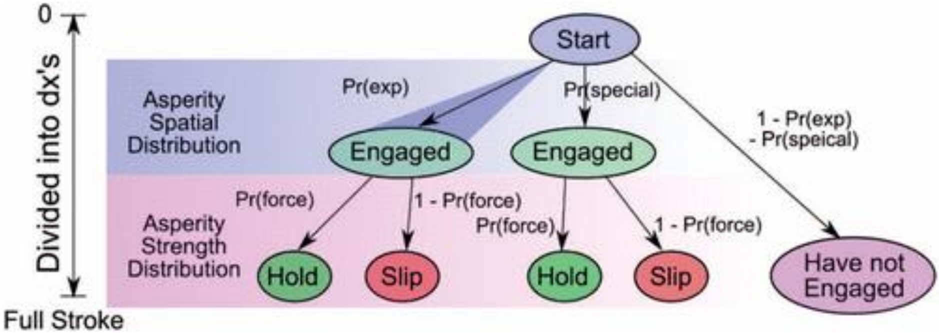
- Original model depends mostly on surface normal and approach angle
- Model breaks down in real world
  - No guarantee which green region will be gripped



Asbeck et al., 2005

# Background – Stochastic Microspine Model

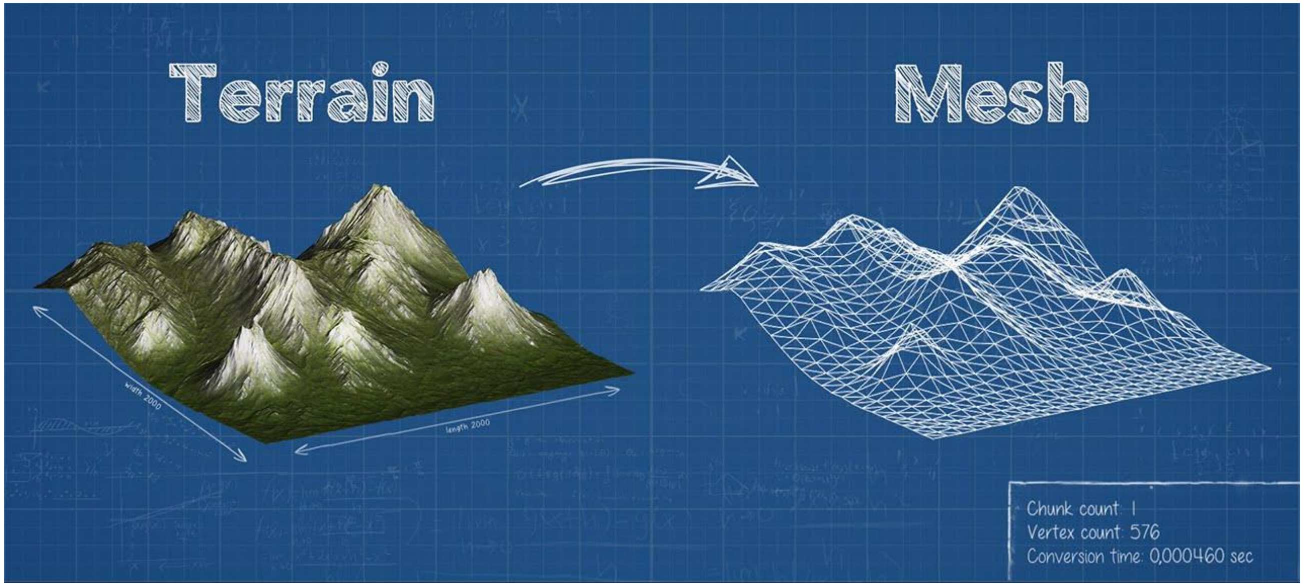
- Extends original model to better simulate real world conditions
- Provides probability of engaging over a planar surface



Jiang et al., 2018

# Objective

- Extend the planar probabilistic microspine model to large scale surface geometry (an arbitrary polygon mesh)
  - From 3D scans or real-time with LiDAR



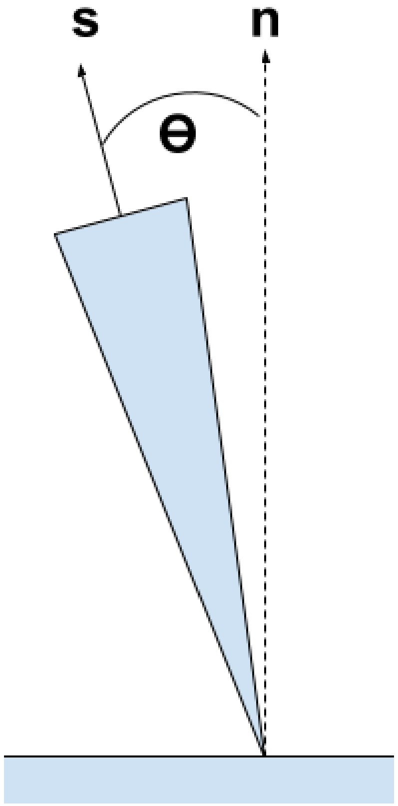
Nakisdashvili, 2016

# Method - Introduction

- We are going to focus on a single spine at first
    - Method extends to all spines
- Operating on a 3D mesh made of triangular or rectangular faces

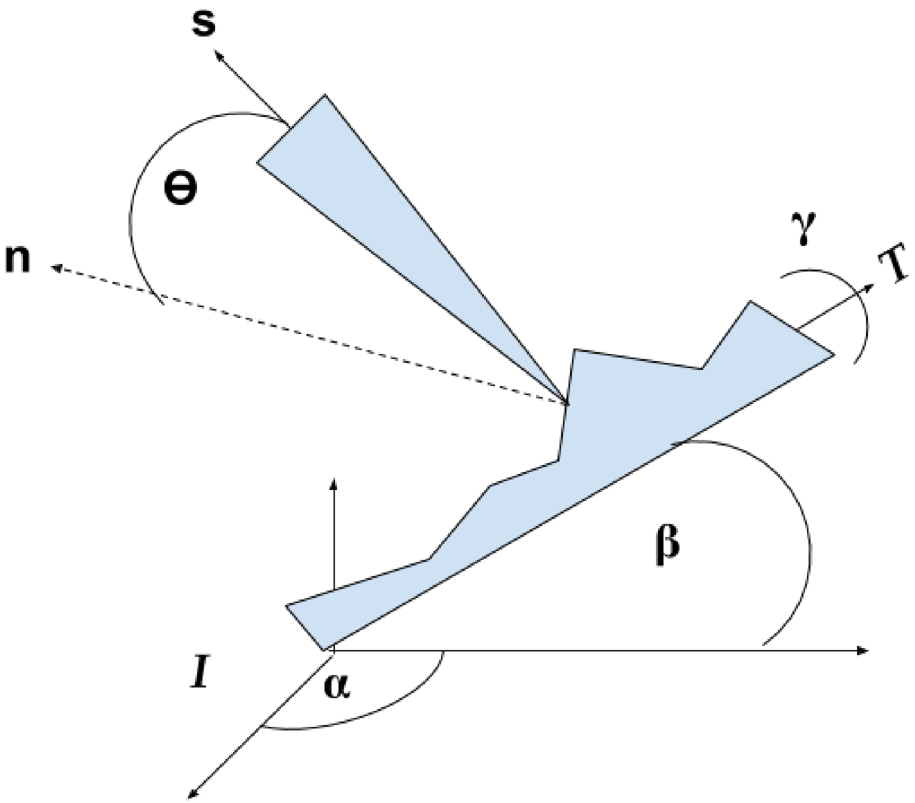
# Method – Spine Geometry

- Spine defined as vector $\boldsymbol{s}$ making angle $\boldsymbol{\theta}$ with surface normal $\boldsymbol{n}$
    - $\boldsymbol{\theta}$ determines probability of grasping, strength of grasp, etc.



# Method – 3D Rotation

- Rotate spine from inertial coordinate frame $\boldsymbol{I}$ into triangular face coordinate frame $\boldsymbol{T}$ by $\boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\gamma}$
    - $\boldsymbol{s}' = \boldsymbol{R}_{\boldsymbol{\alpha},\boldsymbol{\beta},\boldsymbol{\gamma}}\boldsymbol{s}$
- $\boldsymbol{\theta} = \boldsymbol{acos}(\boldsymbol{n} \cdot \boldsymbol{s}')$
- Plug $\boldsymbol{\theta}$ into model
    - Provides important values like holding force for a face

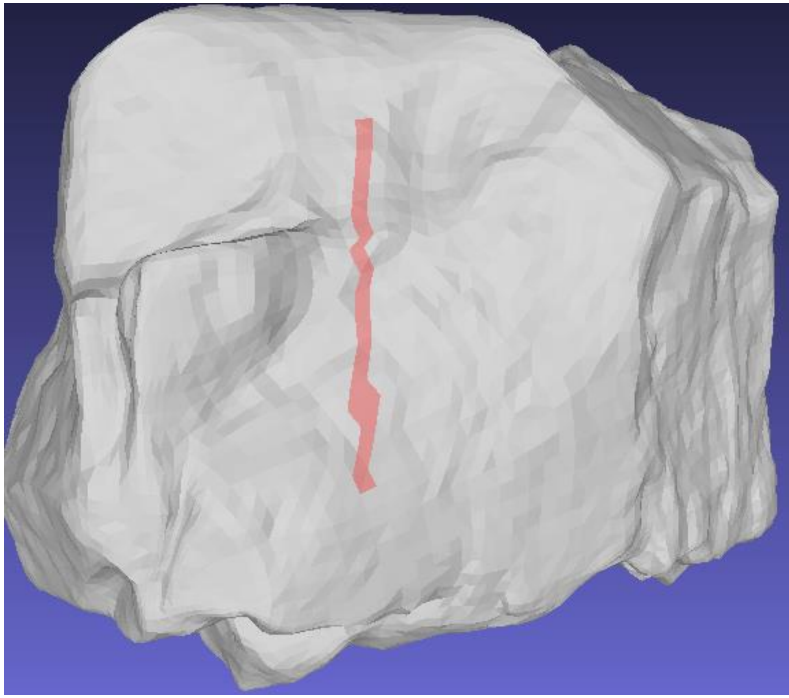


# Method – Probabilistic Contact

- We use Jiang et al.'s stochastic model to model probability of a spine grasping a planar face $f_n$ in a mesh
  - $P(f_n = T)$; Probability of grasping face $n$
  - $P(f_n = F)$; Probability of not grasping face $n$
  - $P(f_n = T) = 1 - P(f_n = F)$
  - Random variables $f_n$ are ***independent*** they do not depend on previous faces

# Method – Probabilistic Contact Chain

- The path of a spine as it retracts forms a chain of surface faces it passes over
  - Contact faces denoted in red
  - $P(f_1), P(f_2), \dots P(f_n) \dots P(f_N)$
    - Probabilities of grasping each face



# Method – Grasp Probability Derivation

- The probability of the spine grasping ***and stopping*** at any particular face $n$ is described as slipping on the previous faces and stopping and grasping on the nth face
  - $P(s_n = T | s_{n-1}, s_{n-2}, \ldots s_1 = F)$
  - Note: stopping $P(s)$ (dependent) is different than gripping $P(f)$ (independent)

# Method – Conditional Dependence

- **If the spine stopped at a previous face, it is not at the current face**
  - $\boldsymbol{P(s_n = T | s_{n-k} = T) = 0 \quad k \in \{1 \ldots n\}}$

# Method – Conditional Independence I

- If the spine slipped past the previous face, the probability of stopping at the current face is the product of the two probabilities of gripping each face ***independently***
  - $\boldsymbol{P(s_2 = T|s_1 = F) = P(f_2 = T)P(f_1 = F)}$
    - Conditional independence
    - Connects $\boldsymbol{P(s)}$ to $\boldsymbol{P(f)}$

# Method – Conditional Independence II

- Extending to all $n$ faces we find

$$P(s_n = T | s_{n-1}, s_{n-2}, \ldots s_1 = F) =$$

$$P(f_n = T)P(f_{n-1} = F)P(f_{n-2} = F) \ldots P(f_1 = F)$$

# Method – Grasp Probability Expression

- Simplifying we get

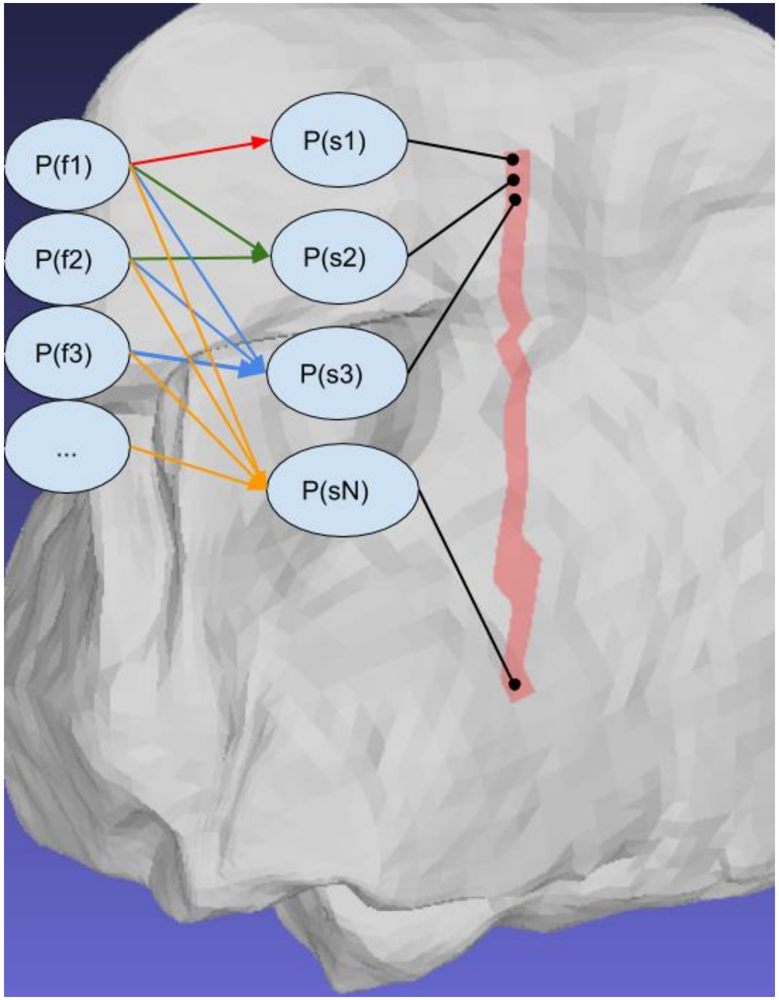
$$P(s_n = T | s_{n-1}, s_{n-2}, \ldots s_1 = F) =$$

$$P(f_n = T) \prod_{i=1}^{n-1} P(f_i = F)$$

  - Recap: this expression gives us the probability of a spine stopping at a specific face $s_n$

# Method – Bayesian Network

- This expression can be represented as an acyclic Bayesian network
  - Visual representation of the math
  - Network nodes are the probabilities of the random variable

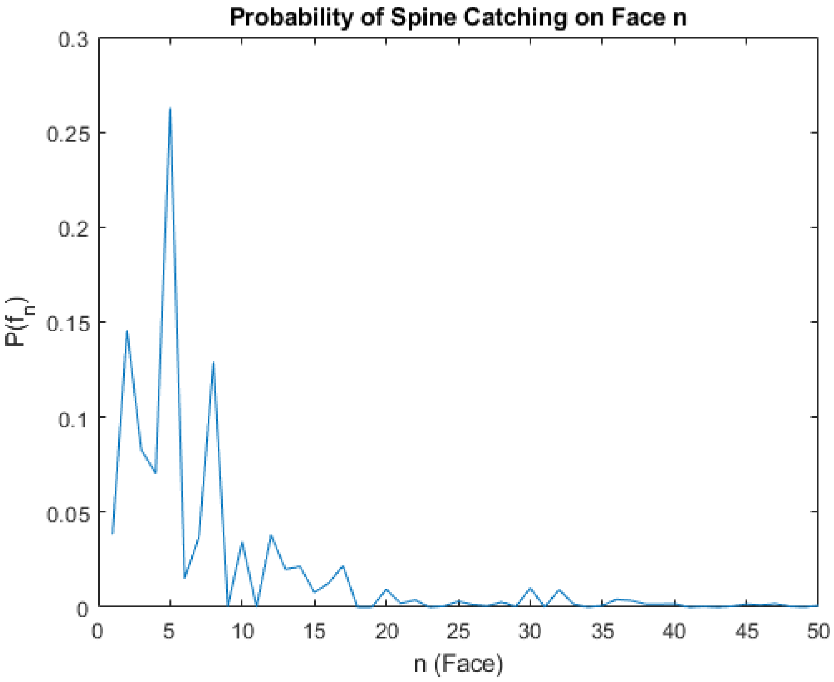


# Method – Belief Propagation

- We can find the probability mass function (PMF) by evaluating

$$P(f_n = T)\prod_{i=1}^{n-1} P(f_i = F)$$

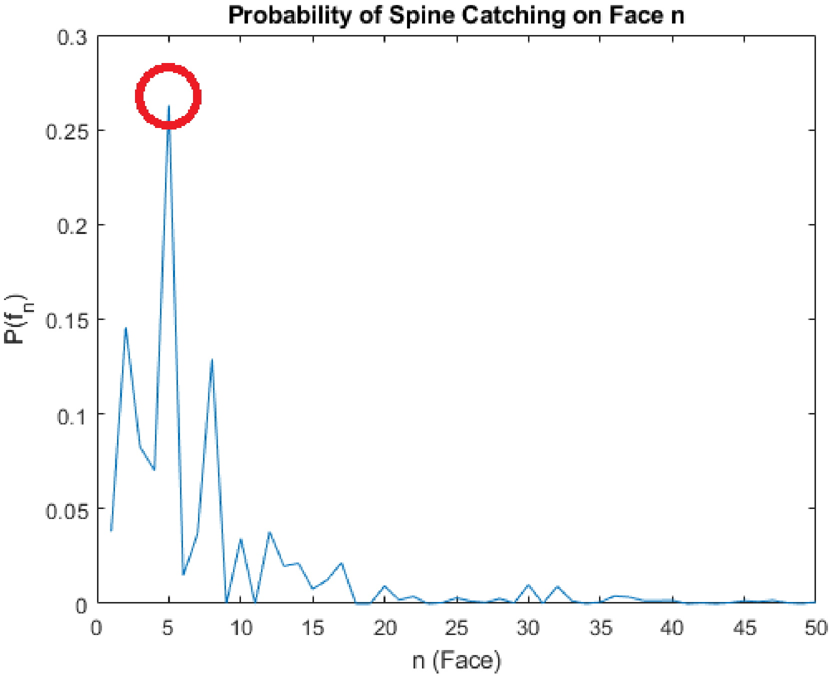
$$for\ n \in \{1, 2, \dots N\}$$



# Method – Maximum Likelihood Estimation

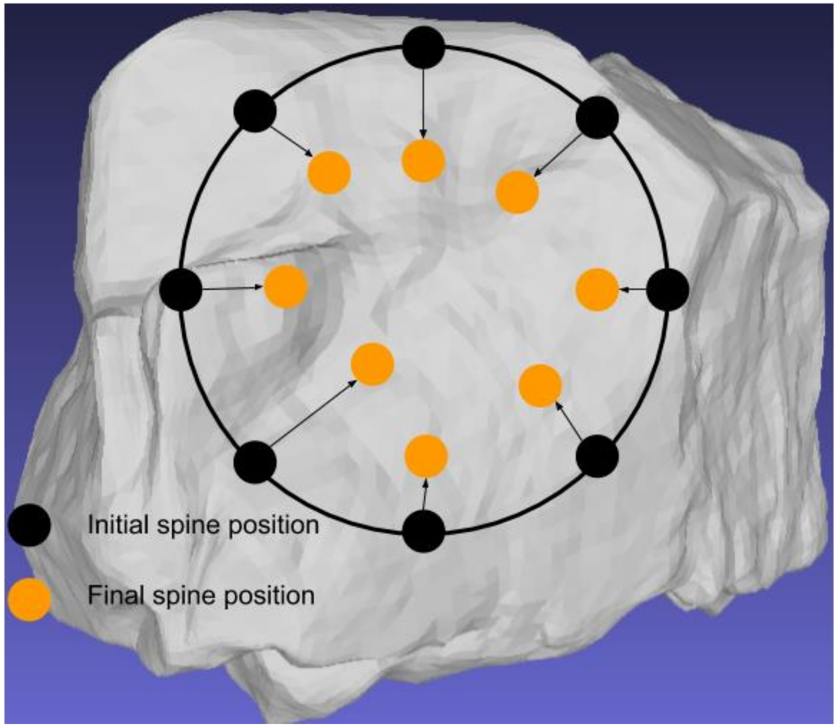
- **We can use maximum likelihood estimation (MLE) to find the most likely face the spine will be on**

$$\max_{n\in\{1,2,\dots N\}} P(s_n) = 5$$



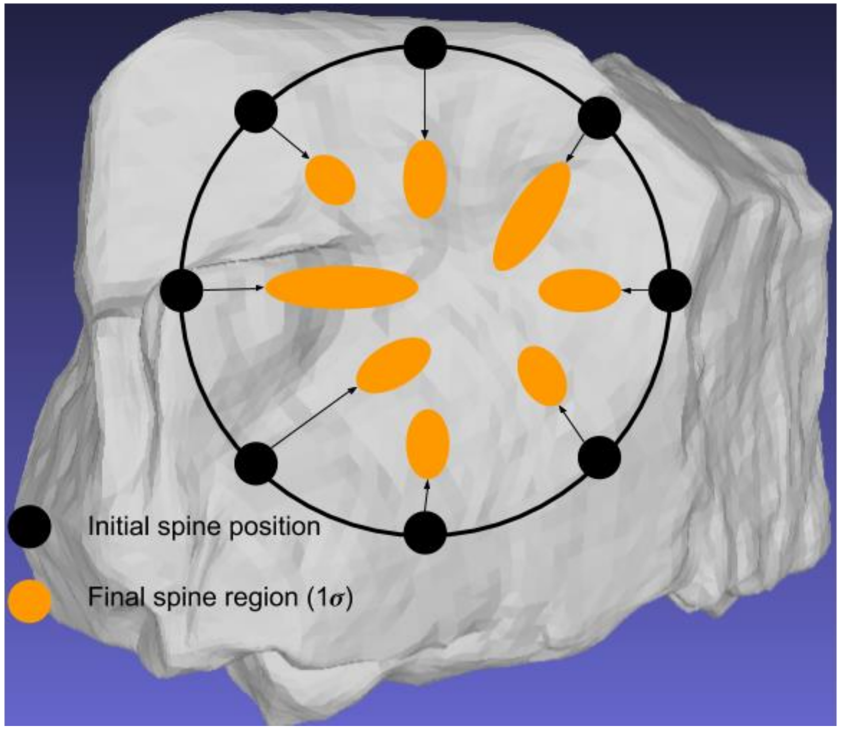
# Method – MLE Gripper Arrangement

- **Running MLE on each spine will produce the most likely arrangement of the gripper**



# Method – High Probability Regions

- More importantly, we have the per-spine probability distribution
- We can define likely grasp regions for each microspine
- We can evaluate a grip by the ***likely regions*** instead of just single points
  - More robust to uncertainty than a single point



# Summary

- We extended probabilistic microspine model to work on large, complex 3D meshes
  - Rotated spines to the 3D mesh faces
  - Derived an expression for a spine stopping at a specific face
  - Found PMF (discrete probability distribution) of spine a stopping over all faces
  - Combined PMFs for all spines to model the entire gripper

# Future Work

- Still a work in progress
- Experimental validation
- Scoring the grip
    - Integration into a motion planner for climbing robots

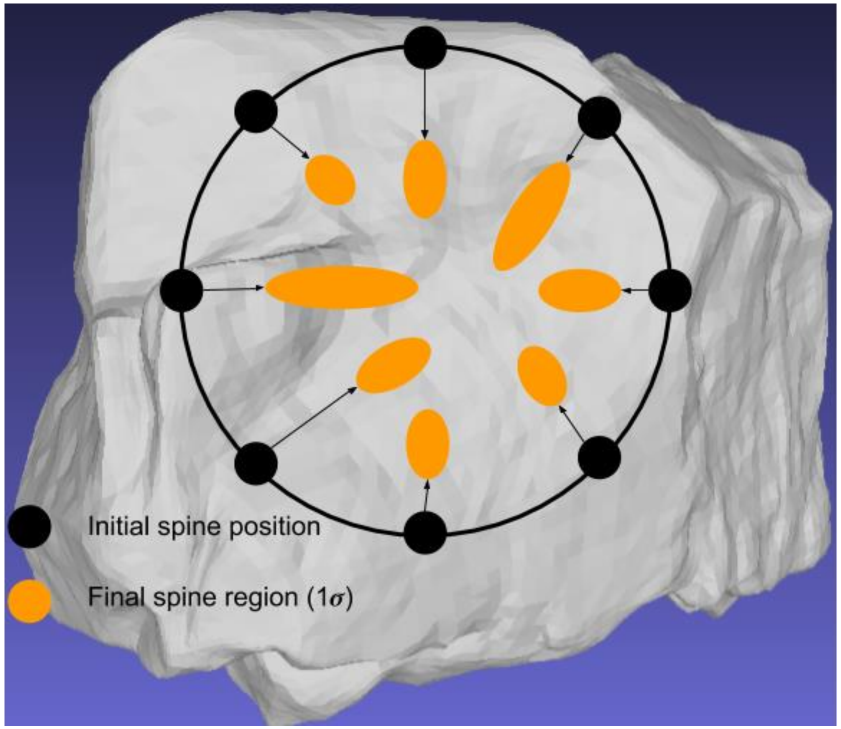
# Questions?

# Future Work - Scoring Grips

- Want a way to “score” grips for robotic climbers
    - Multiple locations to grip, scoring lets us select the best location to place the gripper
    - Is a grip risky? How much force/torque can it hold?

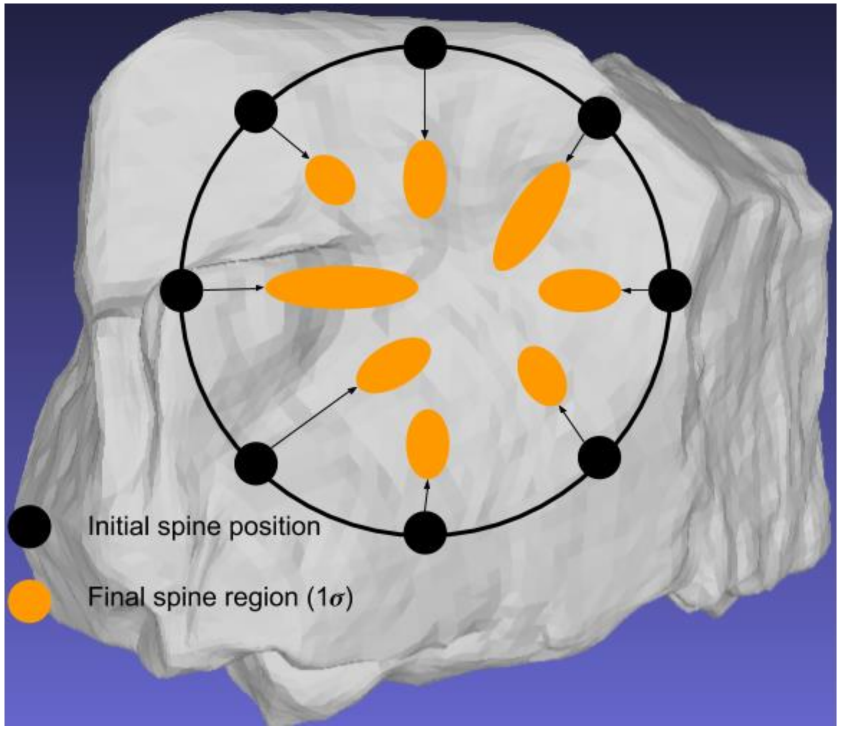
# Future Work - Scoring Grips

- Find ***k*** most likely gripper configurations by permuting most likely spine configurations



# Future Work - Scoring Grips

- Score each of the ***k*** gripper configurations based on criteria
  - Min lateral holding torque
  - Mean normal holding force
  - Etc.



# Future Work - Scoring Grips

- Gripper configuration score fed to motion planner
    - Avoid risky grips