System Design Issues for Virtual Reality SImulations with Haptic Displays

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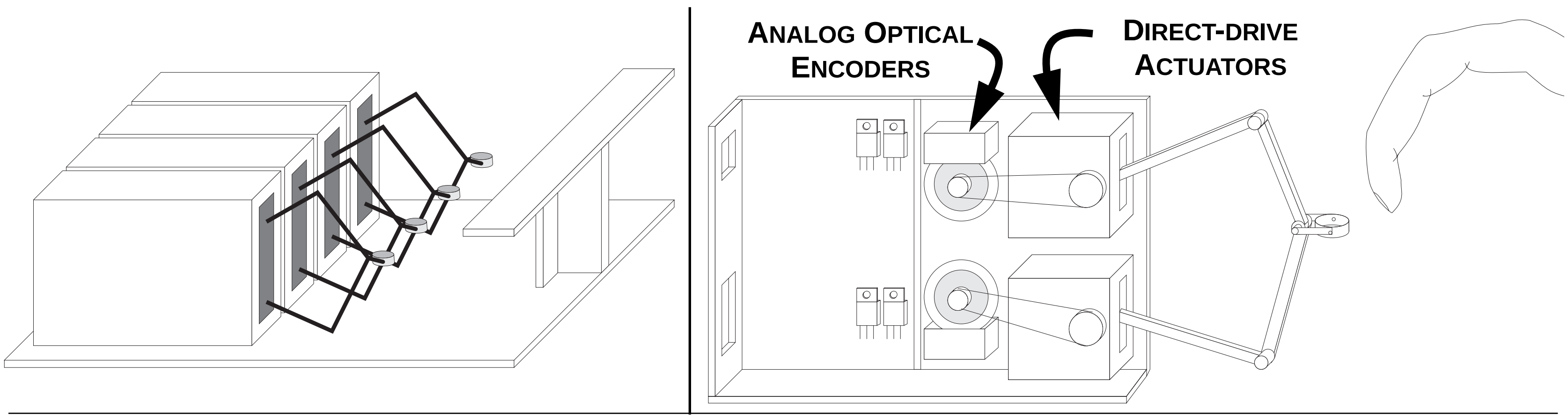
UW Fingertip Haptic Display (FHD)

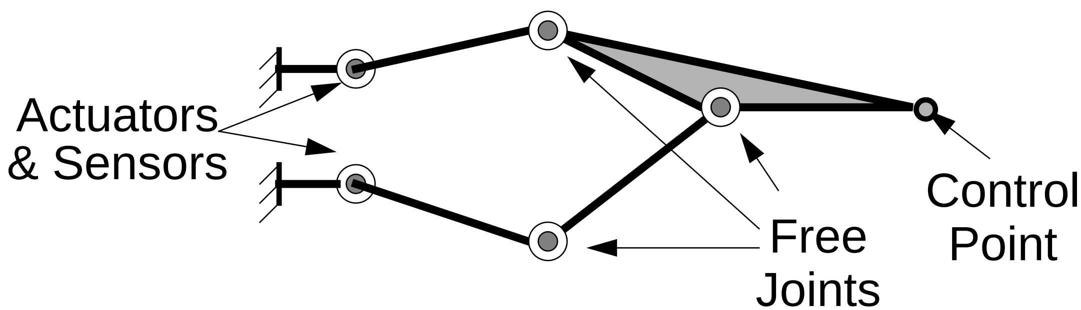
Research Goal:

- Explore the utility of a FHD in the detection of surface shapes and contours

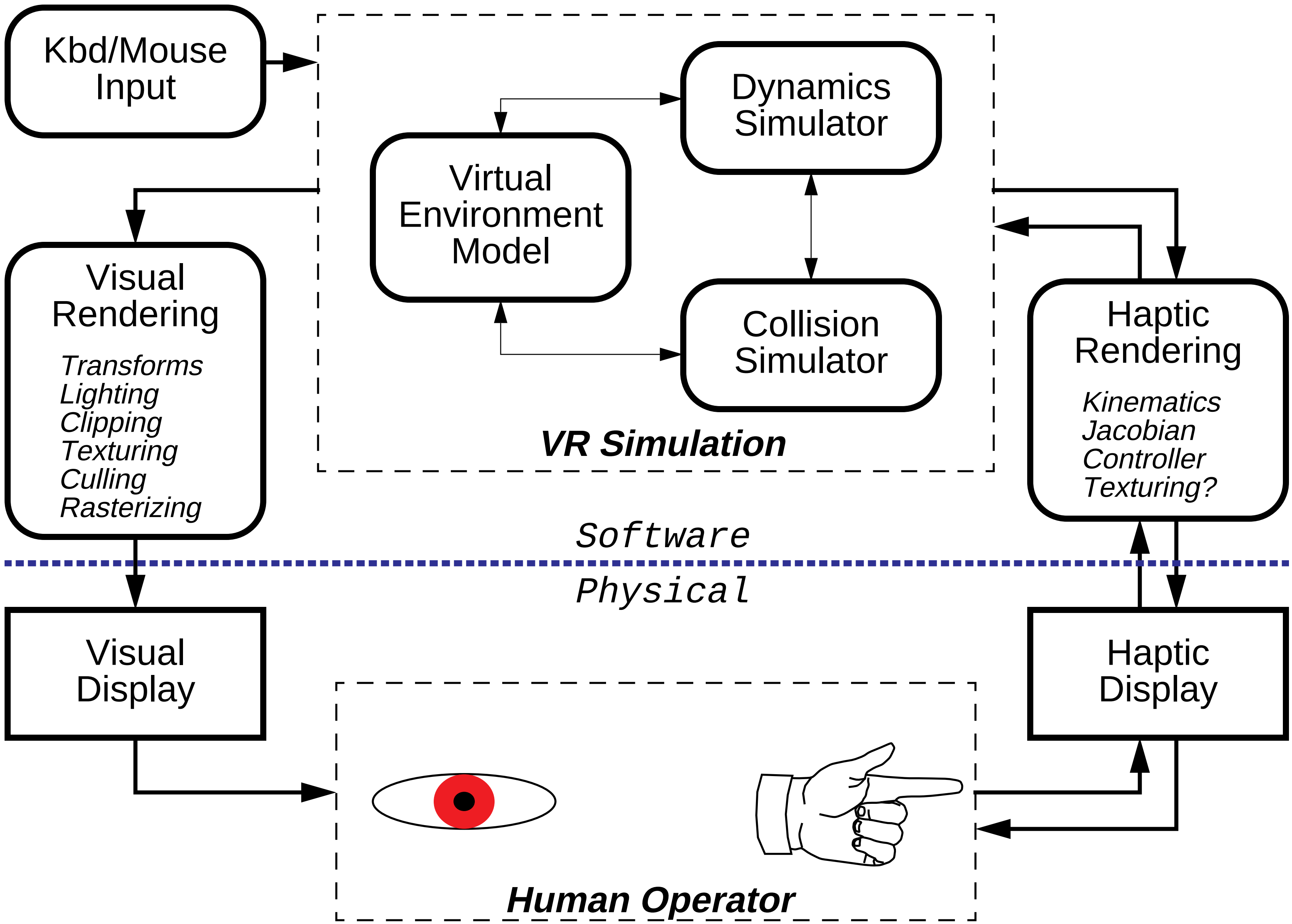
Implementation

- Flexion/extension motion of the human finger
- Mechanical design to allow multiple FHD’s to be used for multiple fingers



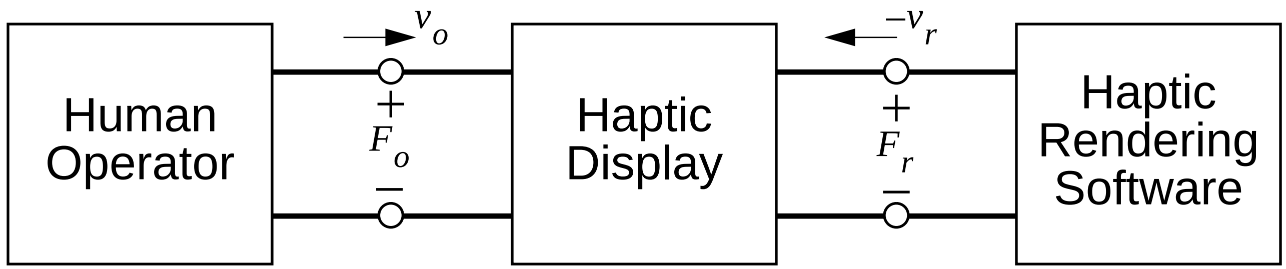


- Project support: Ford Motor Company., Intel. Corp.



Kbd/Mouse Input
Dynamics Simulator
Virtual Environment Model
Collision Simulator
VR Simulation
Visual Rendering
Transforms
Lighting
Clipping
Texturing
Culling
Rasterizing
Haptic Rendering
Kinematics
Jacobian
Controller
Texturing?
Software
Physical
Visual Display
Haptic Display
Human Operator

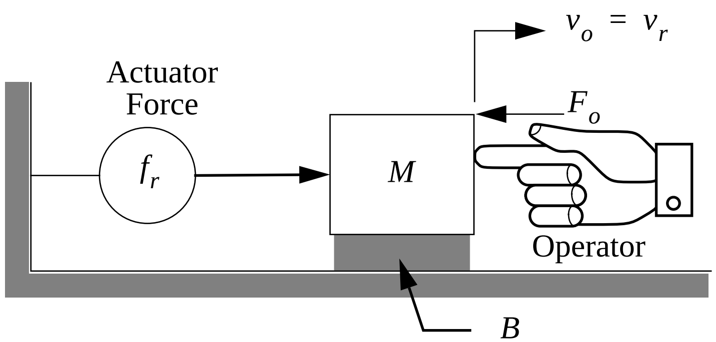
Two-port haptic display model[1]



Hybrid Matrix, H satisfies:
$$\begin{bmatrix} F_o \\ -v_r \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} v_o \\ F_r \end{bmatrix}$$

The ideal "transparent" haptic display has H:
$$\begin{bmatrix} F_o \\ -v_r \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} v_o \\ F_r \end{bmatrix}$$

Simplified 1-axis haptic device model:

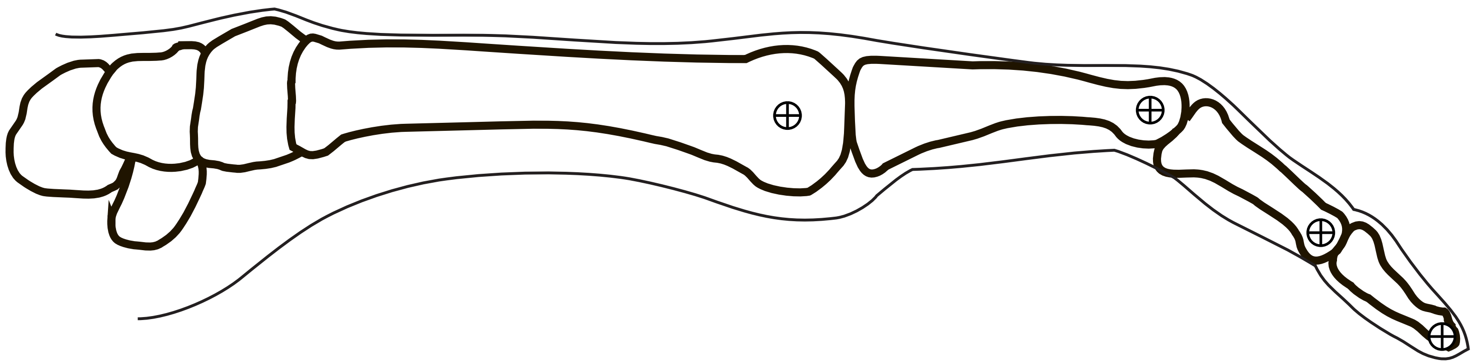


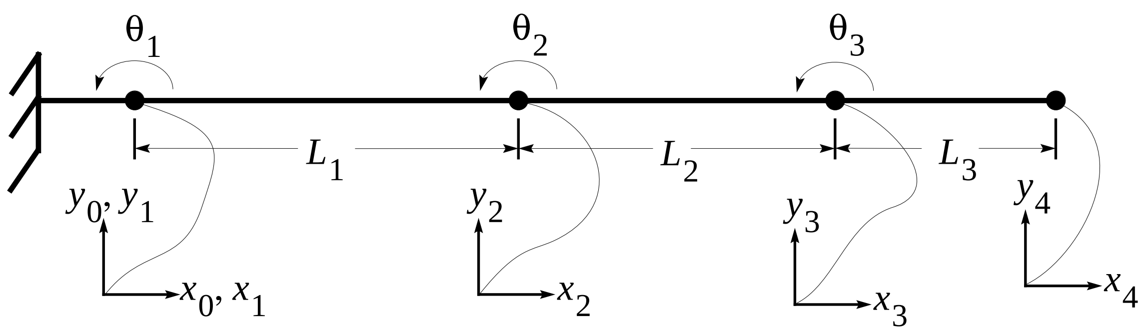
$$F_o = F_r + (B \cdot v_o) + \left(M \cdot \dot{v}_o\right)$$

$$\begin{bmatrix} F_o \\ -v_r \end{bmatrix} = \begin{bmatrix} Ms + b & 1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} v_o \\ F_r \end{bmatrix}$$

1. Adams & Hannaford, 1998.

Kinematic Model of Finger Flexion/Extension





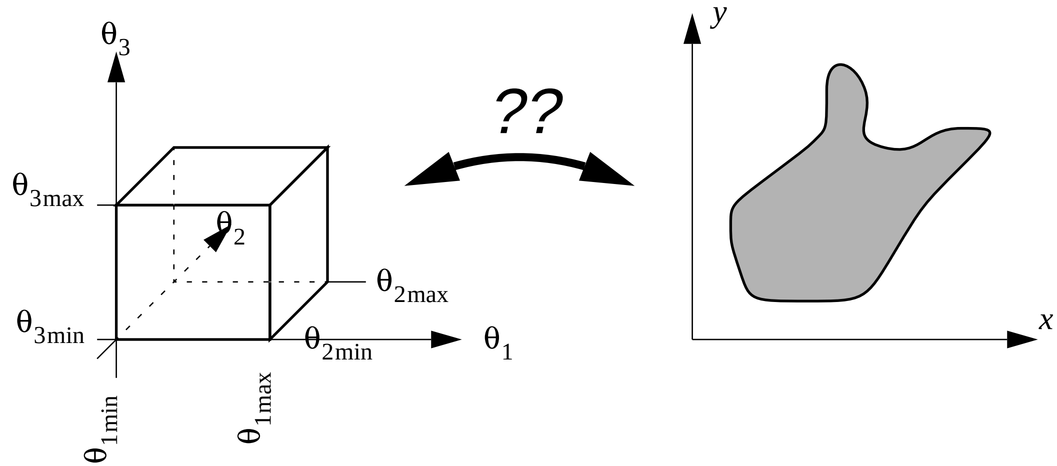
Kinematic Parameters

$$\begin{bmatrix} L_1 & \theta_{1MIN} & \theta_{1MAX} \\ L_2 & \theta_{2MIN} & \theta_{2MAX} \\ L_3 & \theta_{3MIN} & \theta_{3MAX} \end{bmatrix}$$

Kinematic Variables

$$\begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix}$$

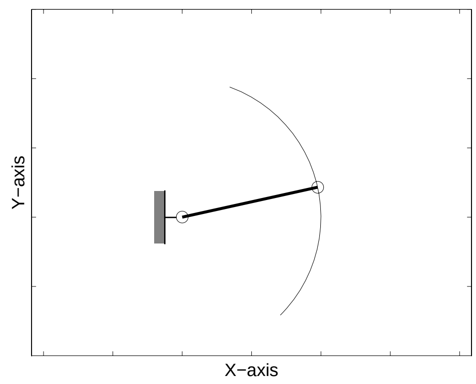
Reachable Workspace:



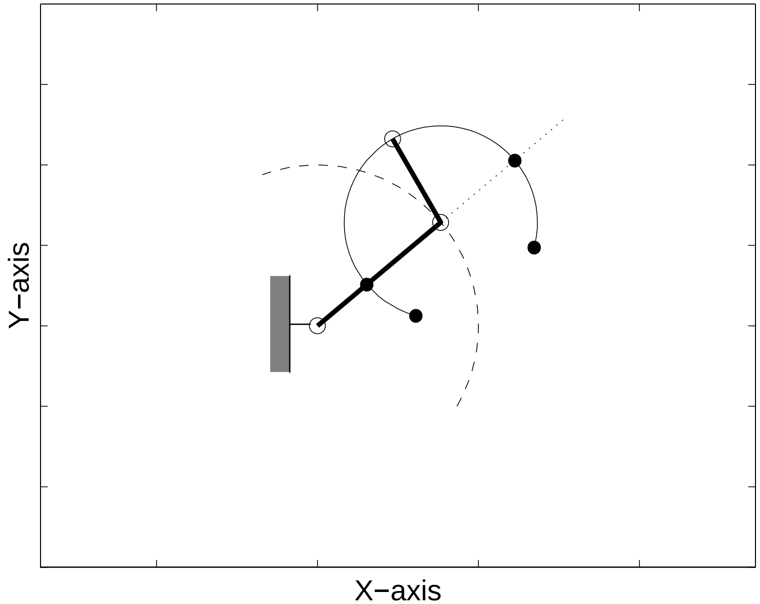
Boundary Representation

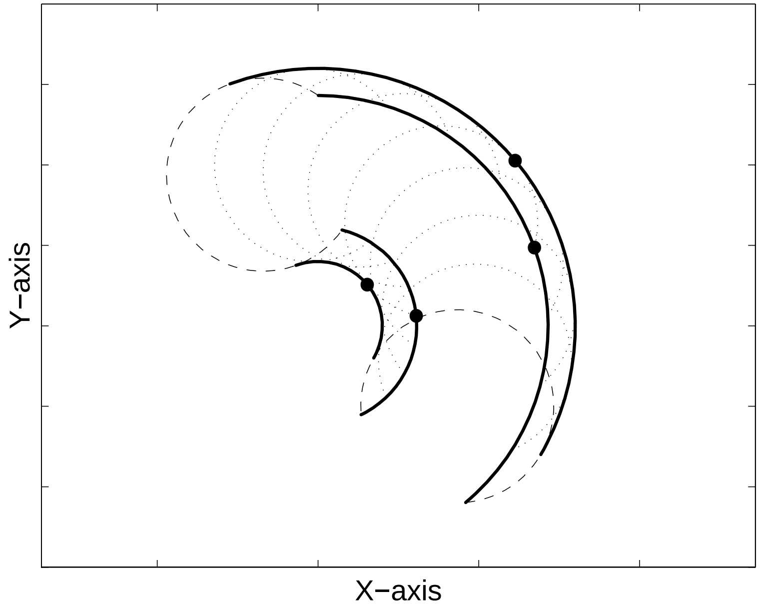
- Geometric boundary representation of reachable workspace
- For a serial mechanism with revolute joints moving in a plane, the boundary will be a series of connected arcs

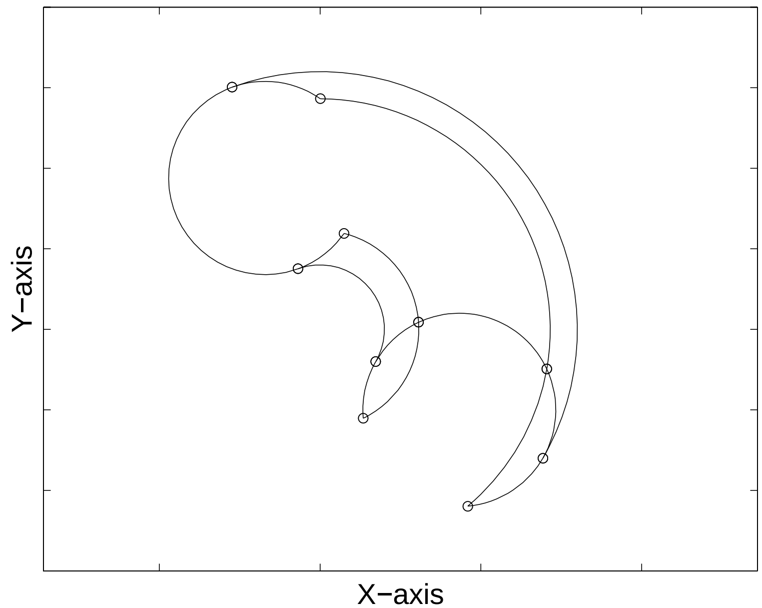
1-DOF Reachable workspace boundary:



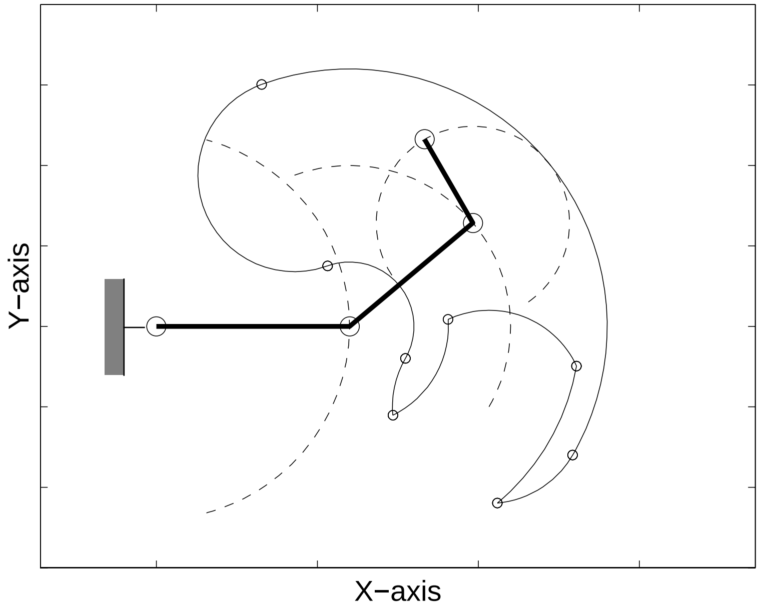
2-DOF reachable workspace boundary

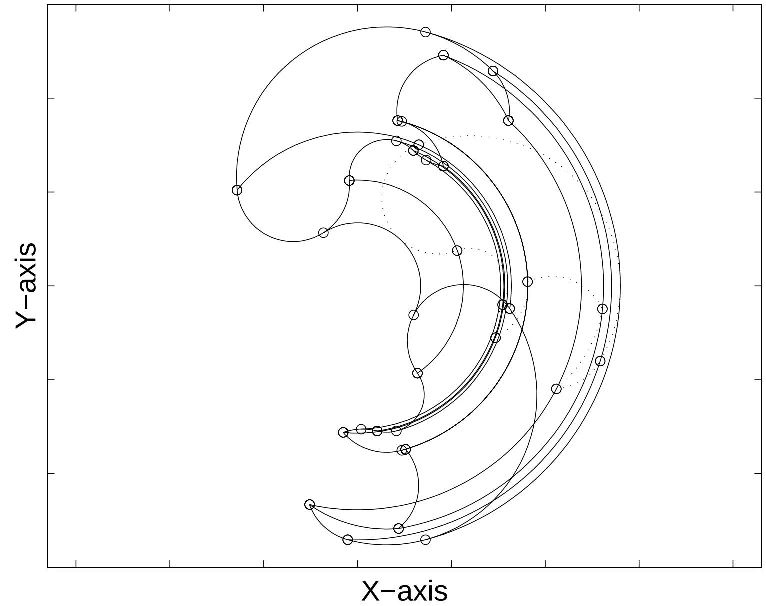




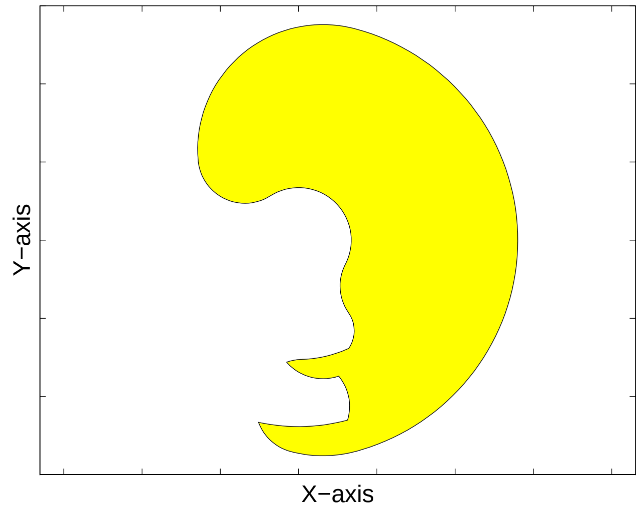


3-DOF Reachable Workspace:





- Resulting Reachable Workspace:

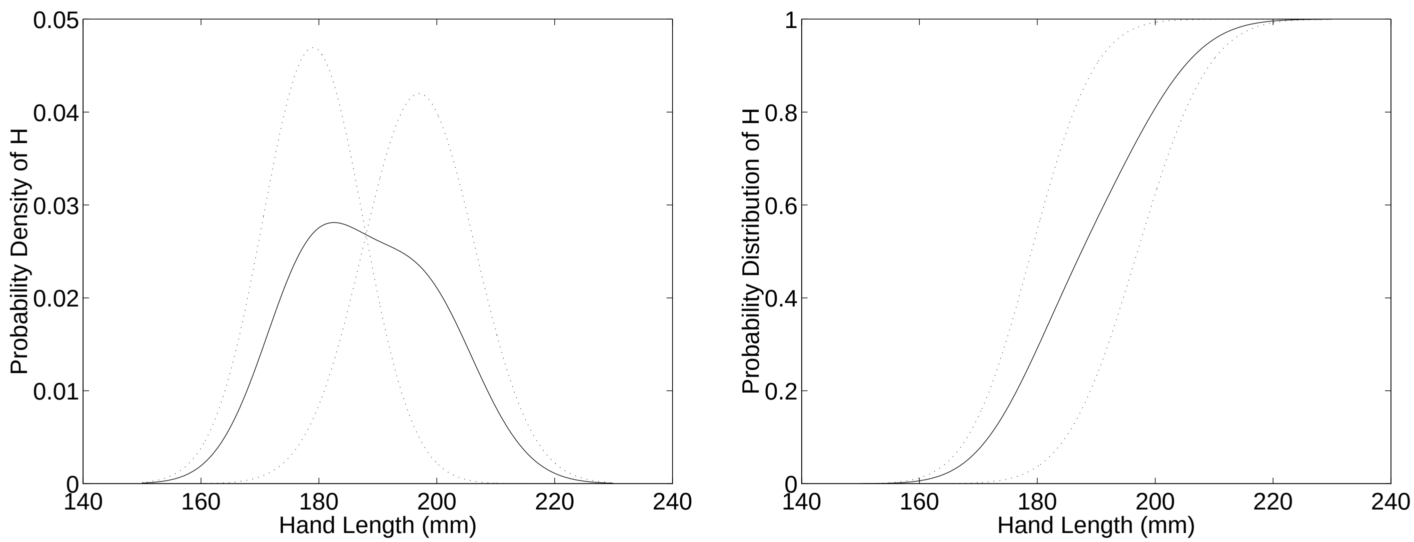


Stochastic Kinematics

- Previous reachable workspace derivation assumes *known* kinematics
- Human hands/fingers vary in size
- Stochastic model of hand length:

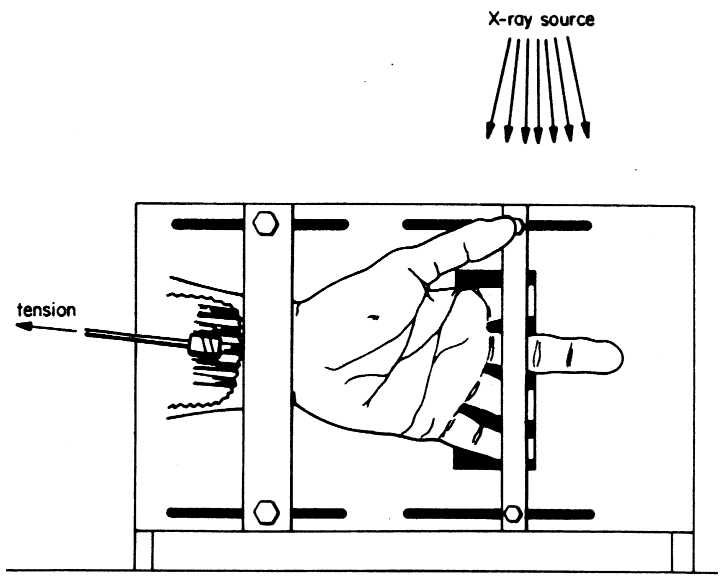
(Adapted from tabular data published in Garrett, 1971)

$$\rho(H) = \frac{\exp\left[\frac{(h-197)^2}{-2\,(9.5)^2}\right]}{2\sqrt{2\pi\,(9.5)^2}} + \frac{\exp\left[\frac{(h-179)^2}{-2\,(8.5)^2}\right]}{2\sqrt{2\pi\,(8.5)^2}}$$



Finger segment length data

- Buchholz data [1992]
  (Hands from 6 cadavers with a "broad spectrum of hand sizes")
- Correlate hand length with finger segment lengths:

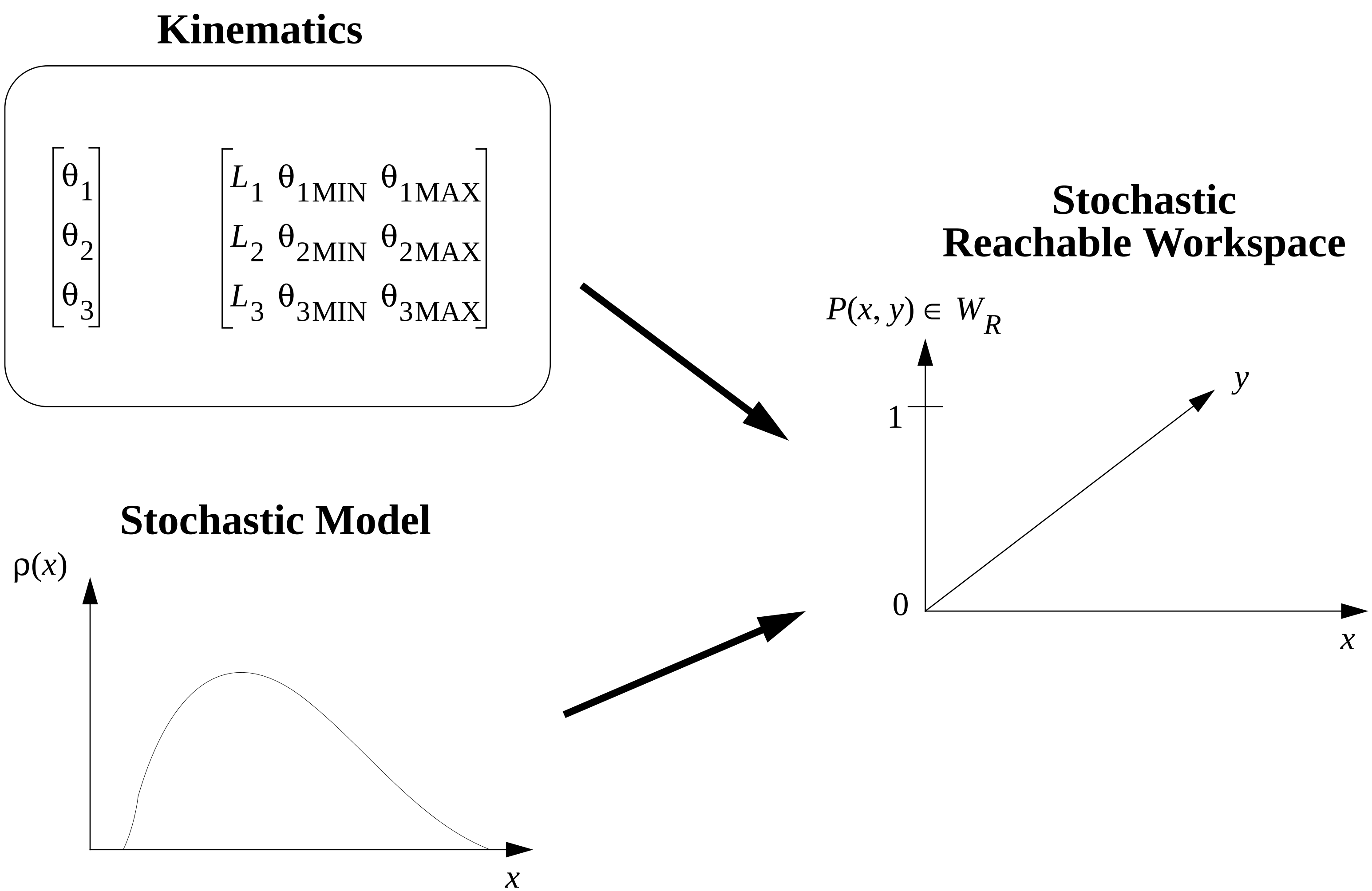


Finger		Proximal Phalanx		Middle Phalanx		Distal Phalanx	
Name	#	Coeff	Error	Coeff	Error	Coeff	Error
First	1	0.245	0.001	0.143	0.003	0.097	0.002
Middle	2	0.266	0.003	0.170	0.003	0.108	0.003
Ring	3	0.244	0.003	0.165	0.002	0.107	0.004
Little	4	0.204	0.002	0.117	0.002	0.093	0.003

- So the link lengths of finger 1 (index finger) of with average hand length would be:

$$\begin{aligned}\begin{bmatrix} l_1 & l_2 & l_3 \end{bmatrix} &= 197\text{mm} \times \begin{bmatrix} 0.245 & 0.143 & 0.097 \end{bmatrix} \\ &= \begin{bmatrix} 48.3 & 28.2 & 19.11 \end{bmatrix}\text{mm}\end{aligned}$$

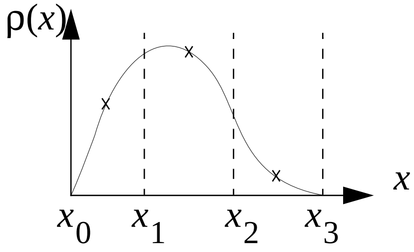
Stochastic Reachable Workspace:



Stochastic Workspace Computation

- Probability density and distribution are related by:

$$P(x_1 < x \le x_2) = \int_{x_1}^{x_2} p(x)dx \qquad (1)$$



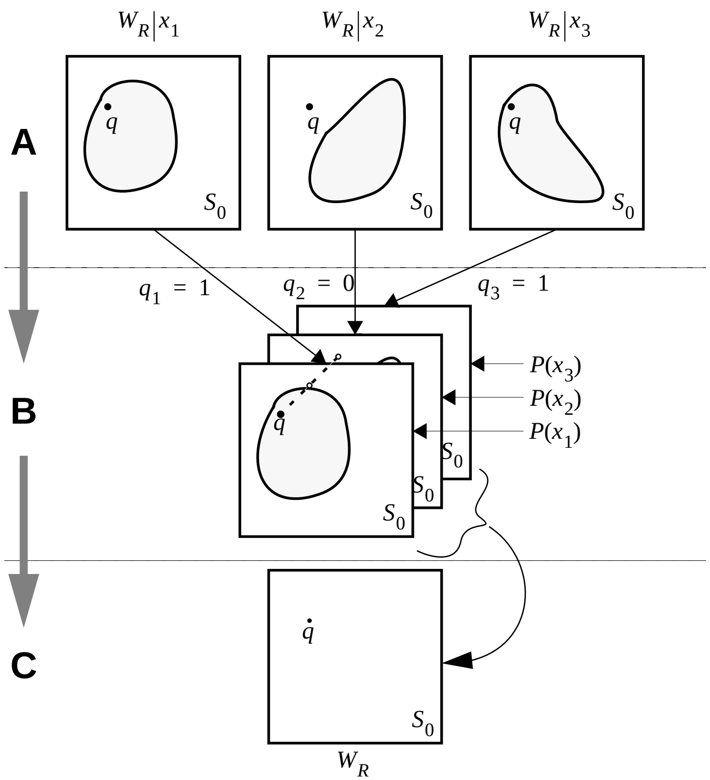
- Piecewise integration of reachable workspace:

$$P(q) = P(q|x_1)P(x_1) + P(q|x_2)P(x_2) + P(q|x_3)P(x_3)$$
$$= (1)\,P(x_1) + (0)\,P(x_2) + (1)\,P(x_3)$$
$$= P(x_1) + P(x_3)$$

Since $\sum_i P(x_i) \equiv 1$

and $P(q|x_i) \in \{0, 1\} \qquad \forall i$

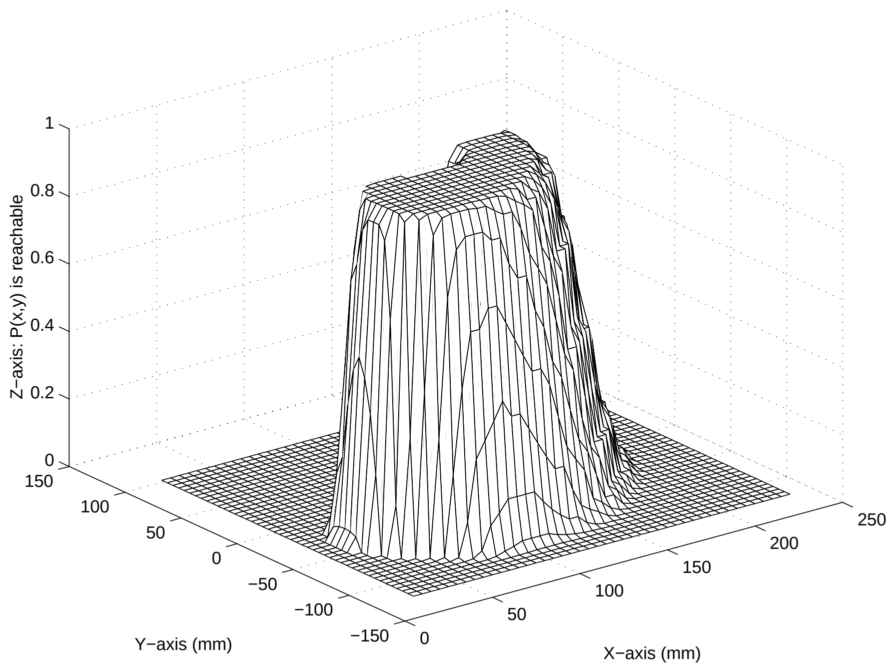
then $0 \le P(q) \le 1$ must be true

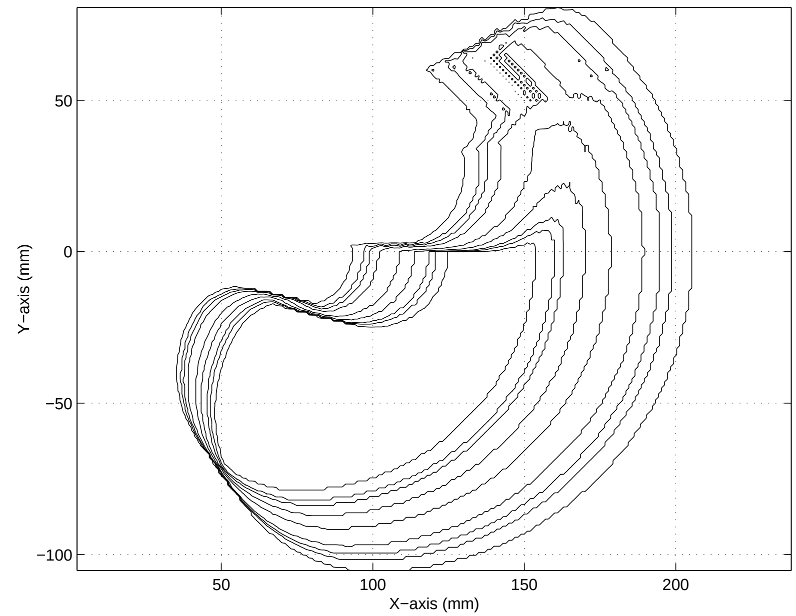


Results: Index Finger Stochastic reachable workspace

- Assume Joint motion ranges of

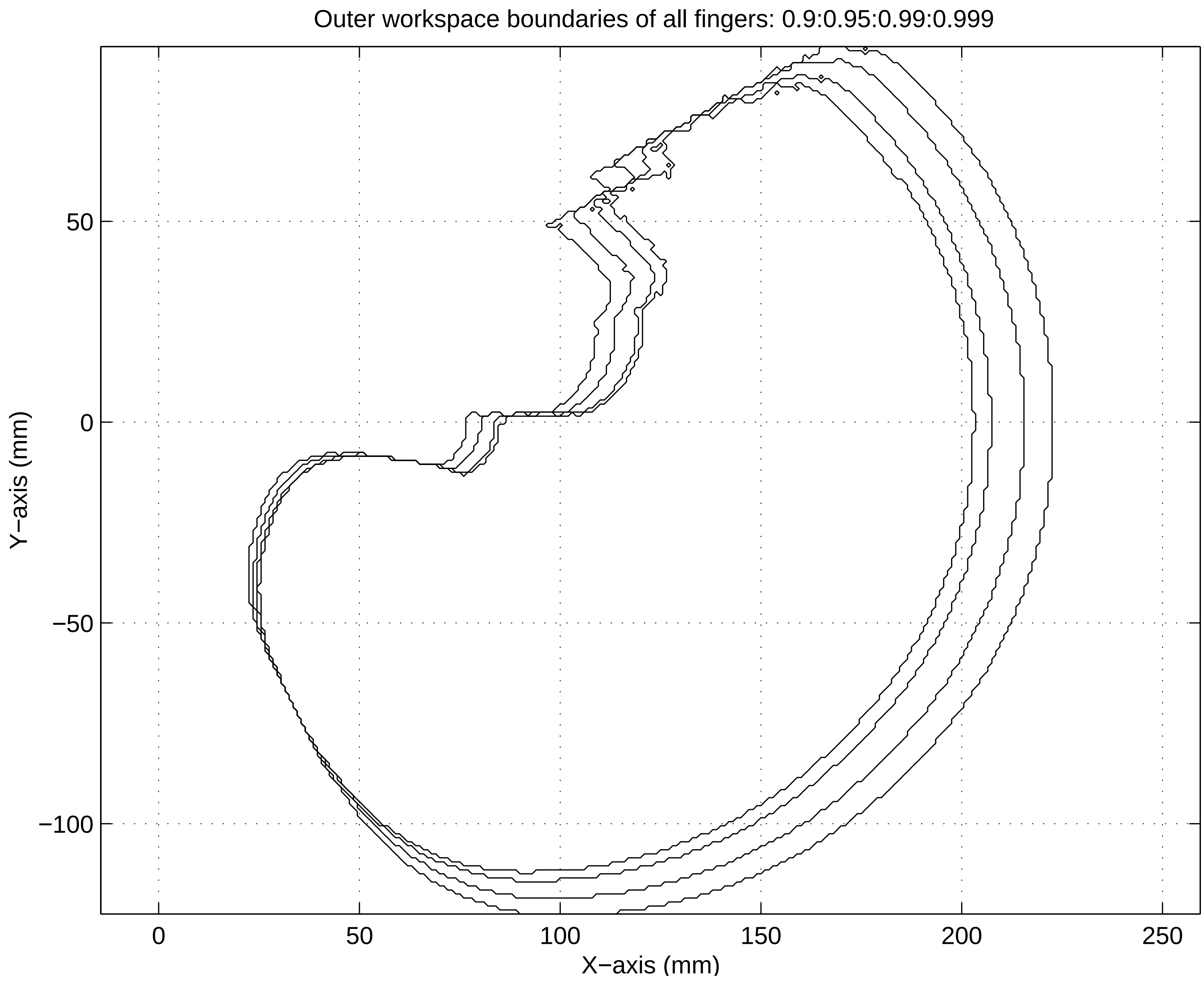
$$-90° \le \theta_1 \le 45°$$
$$-120° \le \theta_2 \le 0°$$
$$-90° \le \theta_3 \le 50°$$





- Contours are at $P(q) = \{0.99, 0.95, 0.90, 0.75, 0.50, 0.20, 0.10, 0.05, 0.01\}$

Results: Boolean combinations of all fingers

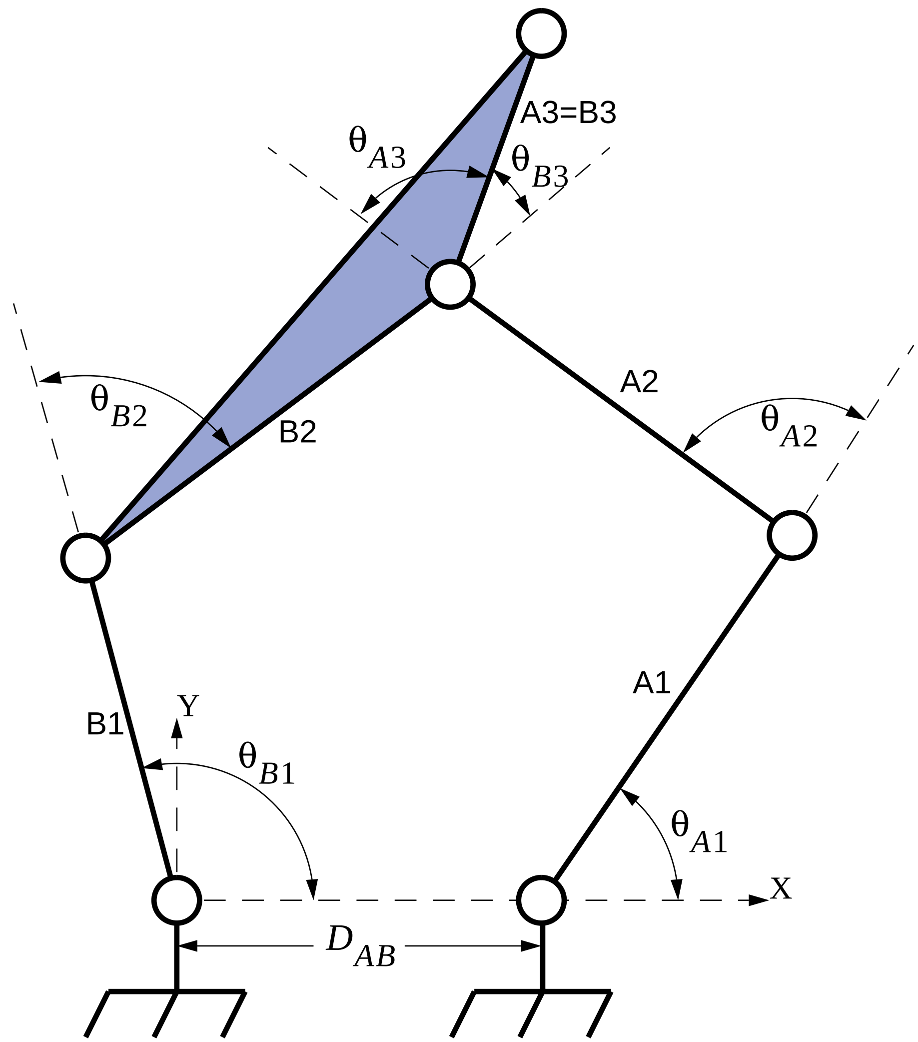


FHD Workspace Design

- Goal: *Just-big-enough* design for accommodating the human finger
  - Lower mass, higher force output (smaller moment arm), higher stiffness
- Extended 5-bar Kinematics and parameters:

Design Parameters

Length	Motion Range	
	Min	Max
$A1$	θ_{A1}min	θ_{A1}max
$A2$	θ_{A2}min	θ_{A2}max
$A3$	θ_{A3}min	θ_{A3}max
$B1$	θ_{B1}min	θ_{B1}max
$B2$	θ_{B2}min	θ_{B2}max
$B3$	θ_{B3}	
D_{AB}		



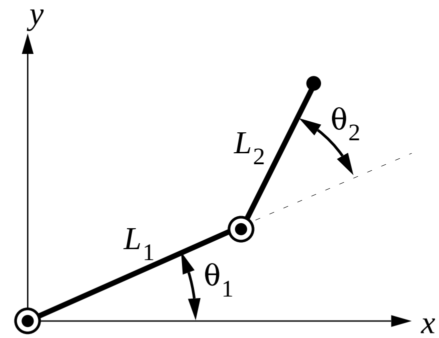
Optimal FHD Design Approach

1. Discretize the design space (5-bar kinematic parameters)
2. Evaluate each possible candidate mechanism’s workspace
3. Choose “best” mechanism

Optimization Goals

- Maximize force output
- Maximize reachable workspace
- Provide “good” force isotropy

Given 2-link serial mechanism with planar revolute joints:



Position & Velocity Relations:

$$x = L_1 \cos(\theta_1) + L_2 \cos(\theta_1 + \theta_2)$$
$$y = L_1 \sin(\theta_1) + L_2 \sin(\theta_1 + \theta_2)$$

$$\theta_2 = \pm \operatorname{acos}\left(\frac{x^2 + y^2 - L_1^2 - L_2^2}{2 L_1 L_2}\right)$$

$$\theta_1 = \operatorname{atan2}\left(\frac{y}{x}\right) \mp \operatorname{acos}\left(\frac{x^2 + y^2 + L_1^2 - L_2^2}{2 L_1 \sqrt{x^2 + y^2}}\right)$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} \frac{\partial x}{\partial \theta_1} & \frac{\partial x}{\partial \theta_2} \\ \frac{\partial y}{\partial \theta_1} & \frac{\partial y}{\partial \theta_1} \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = J(\theta)\dot{\theta}$$

$$J(\theta) = \begin{bmatrix} -L_1 \sin(\theta_1) - L_2 \sin(\theta_1 + \theta_2) & -L_2 \sin(\theta_1 + \theta_2) \\ L_1 \cos(\theta_1) + L_2 \cos(\theta_1 + \theta_2) & L_2 \cos(\theta_1 + \theta_2) \end{bmatrix}$$

Applications of the Jacobian:

- Velocity Controller: $\dot{\theta} = J^{-1}(\theta)\dot{X}$ (singularities!)
- Force Controller: $\tau = J^T(\theta)F$

Singularity analysis

- Singularities in $J(\theta)$ occur as a function of θ and define the positions at which the mechanism loses its ability to move in one or more cartesian directions.
- The Jacobian is singular when $\det(J(\theta)) = 0$
- Singular values of J:

$$\sigma_i = \sqrt{\lambda_i} \text{ where } \lambda_i \text{ is the } i^{\text{th}} \text{ eigenvalue of } \left[J^T(\theta)J(\theta)\right] \quad (2)$$

Uses of singular values

- $\sigma_{\text{max}}(\theta)$ and $\sigma_{\text{min}}(\theta)$ are proportional to the max/min possible Cartesian velocity
- $\dfrac{1}{\sigma_{\text{max}}(\theta)}$ and $\dfrac{1}{\sigma_{\text{min}}(\theta)}$ are proportional to the min/max possible Cartesian force
- $\dfrac{\sigma_{\text{min}}}{\sigma_{\text{max}}}(\theta)$ defines the isotropy of velocity/force output

FHD Design Optimization Approach

- Parameter space reduction: 18 parameters reduced to 8 control variables
- Define A_{WR} as the area of the portion of reachable workspace with isotropy >= 0.25
- Define $\widehat{F_{min}}$ as the lowest minimum force $\left(\frac{1}{\sigma_{max}(\theta)}\right)$ in the entire workspace, A_{WR}
- Objective Function: $\mathrm{MAX}(A_{WR} \times \widehat{F_{min}})$

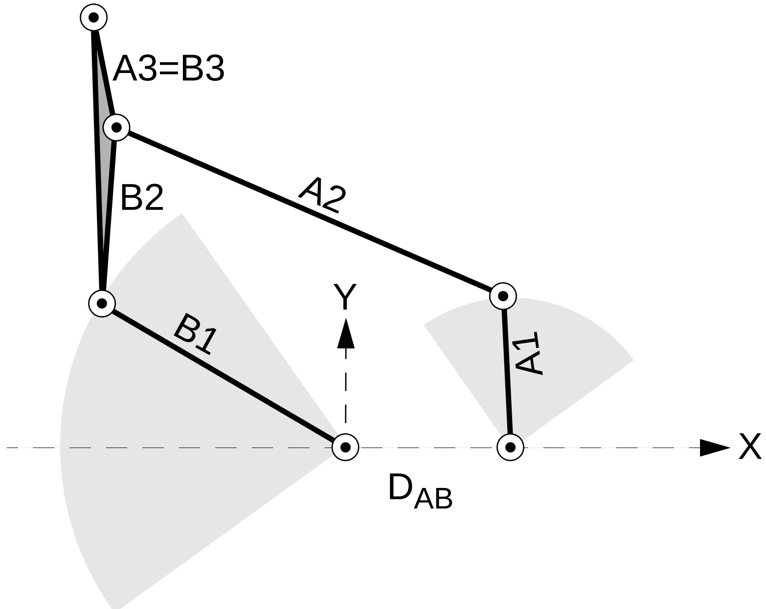
$$J(\theta) = \begin{bmatrix} -B_1 \sin(\theta_{B1}) + \dfrac{B_1 B_3 \sin(\theta_{B1} + \theta_{B3} + \alpha)\sin(\theta_{B1} - \theta_{A1} - \theta_{A2})}{B_2 \sin(\theta_{B1} + \theta_{B2} - \theta_{A1} - \theta_{A2})} & \dfrac{A_1 B_3 \sin(\theta_{B1} + \theta_{B3} + \alpha)\sin(\theta_{A2})}{B_2 \sin(\theta_{B1} + \theta_{B2} - \theta_{A1} - \theta_{A2})} \\ B_1 \cos(\theta_{B1}) - \dfrac{B_1 B_3 \cos(\theta_{B1} + \theta_{B3} + \alpha)\sin(\theta_{B1} - \theta_{A1} - \theta_{A2})}{B_2 \sin(\theta_{B1} + \theta_{B2} - \theta_{A1} - \theta_{A2})} & \dfrac{-A_1 B_3 \cos(\theta_{B1} + \theta_{B3} + \alpha)\sin(\theta_{A2})}{B_2 \sin(\theta_{B1} + \theta_{B2} - \theta_{A1} - \theta_{A2})} \end{bmatrix} \quad (3)$$

$$F_{min} = \left[0.5\left(J_{11}^2 + J_{12}^2 + J_{21}^2 + J_{22}^2\right) + \sqrt{0.25\left(J_{11}^2 + J_{21}^2 - J_{12}^2 - J_{22}^2\right)^2 + \left(J_{11}^2 J_{12}^2 + J_{21}^2 J_{22}^2\right)^2}\right]^{-\frac{1}{2}} \quad (4)$$

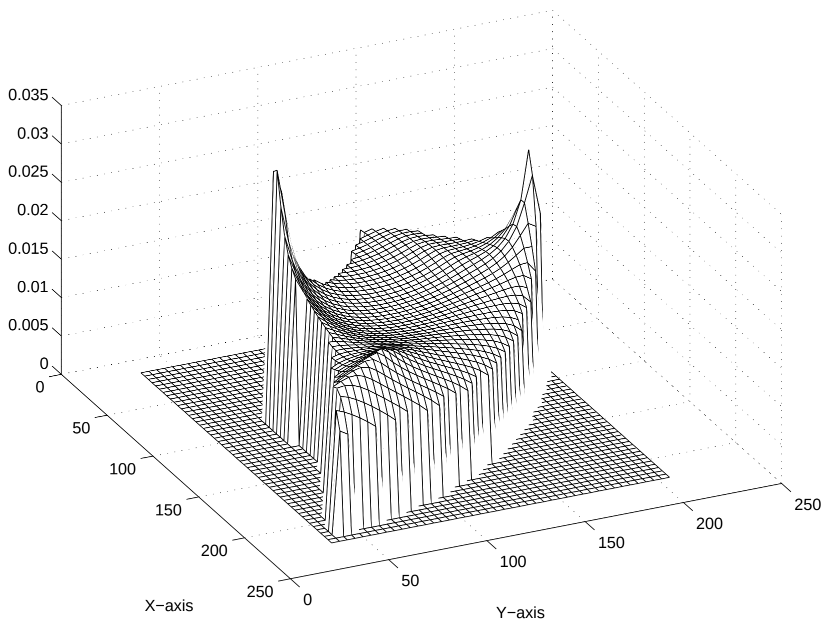
$$ITP = \frac{F_{min}}{\left(F_{min} = \left[0.5\left(J_{11}^2 + J_{12}^2 + J_{21}^2 + J_{22}^2\right) - \sqrt{0.25\left(J_{11}^2 + J_{21}^2 - J_{12}^2 - J_{22}^2\right)^2 + \left(J_{11}^2 J_{12}^2 + J_{21}^2 J_{22}^2\right)^2}\right]^{-\frac{1}{2}}\right)} \quad (5)$$

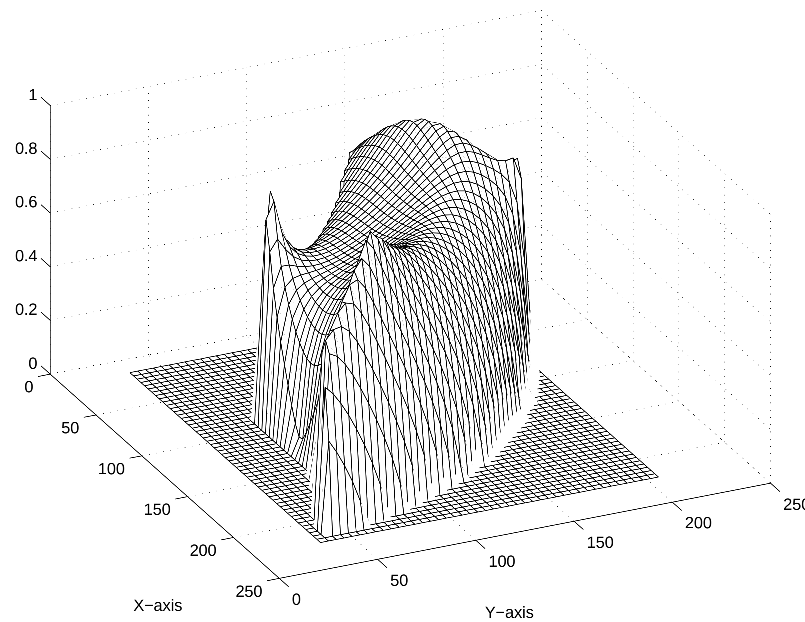
- Optimization process was divided among ~15 CPU's
- Runtime was ~48 hours

Kinematic Optimization Results

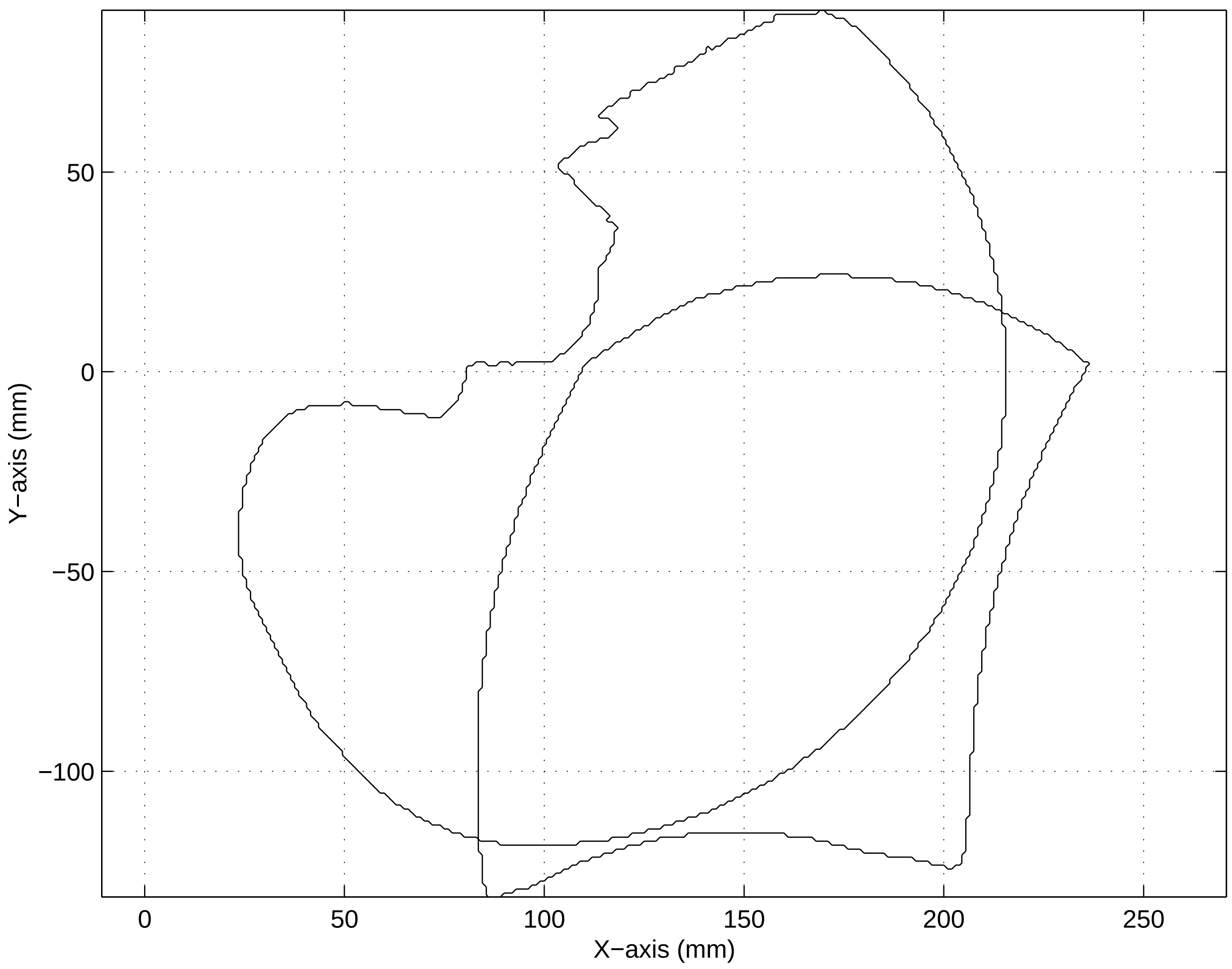


Link	Len (mm)	Min (Deg)	Max (Deg)
A1	53	35	125
A2	150	0	160
A3	40	-160	-5
B1	100	125	215
B2	63	-160	0
B3	40	15	
Dab	58	—	





Comparison of finger and FHD workspaces:



FHD computing environment

- Solaris 2.6-x86 running on 200MHz quad PentiumPro
  - Dell server with 512MB RAM, 0.5MB Cache/chip, 9GB UltraSCSI disk
- Tech80 ISA card with
  - On-board timer/interrupt controller
  - On-board 48-line digital I/O port
  - Four IP daughter module slots
- Encoder IP Module
  - Supports 6 encoder axis
  - Programmable digital filters for encoder inputs
  - Supports wrap-around interrupts, and error detection interrupts
- DAC IP Module
  - Eight 12-bit DAC channels
- Driver
  - open()/close() routines
  - mmap() routine to map kernel pages for Encoder/DAC I/O
  - ioctl() routine to configure interrupt timer, DIO, encoders and DAC, etc.
- Results so far:
  - Interrupt latency 10-24us (12us mean, 3us sdev)

“Hydra” Graphics software:

- 1989-90: Implemented at JPL as an SGI GL application on SGI IRIS-4D system
  - Used for predictive and preview displays, video overlays
- Loads geometry from data file at start-up
- Supports interactive geometry modification via network connections
- Supports high speed joint motion updates via shared memory
- UW:1991-97: Used for design visualization and debugging of kinematics software

Current activities:

- VRML import from MCAD system
- Port from GL to OpenGL
- Add in basic dynamics/collision modules

Problems with using Solaris Unix

- Scheduler
- Interrupt<->Processor assignment
- Direct thread scheduling control desirable
- OpenGL support
- Cache coherency issues (SMP)

Computing Environment Issues

- Real-time computing environment
- Model format (representation)
- CAD/VR Data interchange (including haptic properties)
- Process partitioning (both simulation and rendering)
- Scaling: SMP and/or network interconnection
- Trade-off of speed vs. accuracy
- Price

Alternative OS environments:

- RT-Linux, QNX/Neutrino, VxWorks, RT-NT?