Lecture 14:
Kinesthetic haptic devices: Higher degrees of freedom

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(This lecture was not given, but the notes are posted for reference)
kinematics
(Hapkit reminder)
transmission

Capstan drive

Friction drive
Hapkit kinematics

\[ r_{\text{pulley}} \theta_{\text{pulley}} = r_{\text{sector}} \theta_{\text{sector}} \]

\[ x_{\text{handle}} = r_{\text{handle}} \theta_{\text{sector}} \]

\[ x_{\text{handle}} = \frac{r_{\text{handle}} r_{\text{pulley}}}{r_{\text{sector}}} \theta_{\text{pulley}} \]
Hapkit force/torque relationships

relationship between force and torque:

\[ \tau = Fr \]

\[ \frac{\tau_{\text{pulley}}}{r_{\text{pulley}}} = \frac{\tau_{\text{sector}}}{r_{\text{sector}}} \]

\[ F_{\text{handle}} = \frac{\tau_{\text{sector}}}{r_{\text{pulley}}r_{\text{handle}}} \]
kinematics
(a more complete introduction)
suggested references

• Introduction to robotics: mechanics and control
  John J. Craig

• Robot modeling and control
  Mark W. Spong, Seth Hutchinson, M. Vidyasagar

• A mathematical introduction to robotic manipulation
  Richard M. Murray, Zexiang Li, S. Shankar Sastry

• Springer handbook of robotics
  B. Siciliano, Oussama Khatib (eds.)
Kinematics

• The study of movement

• The branch of classical mechanics that describes the motion of objects without consideration of the forces that cause it

• Why do you need it?
  – Determine endpoint position and/or joint positions
  – Calculate mechanism velocities, accelerations, etc.
  – Calculate force-torque relationships
degrees of freedom

• Number of independent position variables needed to in order to locate all parts of a mechanism

• DOF of motion

• DOF of sensing

• DOF of actuation

• The DOF of a mechanism does not always correspond to number of joints
it will help to prototype!

round head paper fasteners

officedepot.com

www.rogersconnection.com/triangles
joints

• Think of a manipulator/interface as a set of bodies connected by a chain of joints

• **Revolute** is the most common joint for robots

From Craig, p. 69
forward kinematics for higher degrees of freedom

for mechanical trackers that use joint angle sensors, you need a map between \textit{joint space} and \textit{Cartesian space}

fwd kinematics: from joint angles, calculate endpoint position
joint variables

Be careful how you define joint positions

Absolute

Relative
absolute forward kinematics

\[ x = L_1 \cos(\theta_1) + L_2 \cos(\theta_2) \]

\[ y = L_1 \sin(\theta_1) + L_2 \sin(\theta_2) \]

(Often done this way for haptic devices)
relative forward kinematics

\[ x = L_1 \cos(\theta_1) + L_2 \cos(\theta_1 + \theta_2) \]

\[ y = L_1 \sin(\theta_1) + L_2 \sin(\theta_1 + \theta_2) \]

(Often done this way for robots)
Inverse Kinematics

• Using the end-effector position, calculate the joint angles necessary to achieve that position

• Not used often for haptics
  – But could be useful for planning/design

• There can be:
  – No solution (workspace issue)
  – One solution
  – More than one solution
example

• Two possible solutions

• Two approaches:
  – algebraic method (using transformation matrices)
  – geometric method

• Your devices should be simple enough that you can just use geometry
computing end-effector velocity

- forward kinematics tells us the endpoint position based on joint positions
- how do we calculate endpoint velocity from joint velocities?
- use a matrix called the Jacobian

\[ \dot{x} = J \dot{q} \]
formulating the Jacobian

multidimensional form of the chain rule:

\[
\begin{align*}
\dot{x} &= \frac{\partial x}{\partial q_1} \dot{q}_1 + \frac{\partial x}{\partial q_2} \dot{q}_2 + \cdots \\
\dot{y} &= \frac{\partial y}{\partial q_1} \dot{q}_1 + \frac{\partial y}{\partial q_2} \dot{q}_2 + \cdots \\
&\vdots
\end{align*}
\]

assemble in matrix form:

\[
\begin{bmatrix}
\dot{x} \\
\dot{y}
\end{bmatrix} =
\begin{bmatrix}
\frac{\partial x}{\partial q_1} & \frac{\partial x}{\partial q_2} \\
\frac{\partial y}{\partial q_1} & \frac{\partial y}{\partial q_2}
\end{bmatrix}
\begin{bmatrix}
\dot{q}_1 \\
\dot{q}_2
\end{bmatrix}
\]

\[
\dot{x} = J \dot{q}
\]
Singularities

• Many devices will have configurations at which the Jacobian is singular

• This means that the device has lost one or more degrees of freedom in Cartesian Space

• Two kinds:
  – Workspace boundary
  – Workspace interior
Singularity Math

• If the matrix is invertible, then it is non-singular.

\[ \dot{\theta} = J^{-1} \dot{x} \]

• Can check invertibility of \( J \) by taking the determinant of \( J \). If the determinant is equal to 0, then \( J \) is singular.

• Can use this method to check which values of \( \theta \) will cause singularities.
Calculating Singularities

Simplify text: \( \sin(\theta_1 + \theta_2) = s_{12} \)

\[
\det(J(\theta)) = \begin{vmatrix}
-L_1s_1 - L_2s_{12} & -L_2s_{12} \\
L_1c_1 + L_2c_{12} & L_2c_{12}
\end{vmatrix}
= (-L_1s_1 - L_2s_{12})L_2c_{12} + (L_1c_1 + L_2c_{12})L_2s_{12}
\]

For what values of \( \theta_1 \) and \( \theta_2 \) does this equal zero?
compute the necessary joint torques

the Jacobian can also be used to relate joint torques to end-effector forces:

\[ \tau = J^T f \]

this is a key equation for multi-degree-of-freedom haptic devices
how do you get this equation?

the **Principle of virtual work**

states that changing the coordinate frame does not change the total work of a system

\[
f \cdot \delta x = \tau \cdot \delta q \\
f^T \delta x = \tau^T \delta q \\
f^T J \delta q = \tau^T \delta q \\
f^T J = \tau^T \\
J^T f = \tau
\]
force generation signals

desired force (in computer)

counts

D/A

volts

amplifiers

voltage or current

actuator

force/torque

transmission & kinematics

endpoint

force/torque

Stanford University

ME 327: Design and Control of Haptic Systems

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Phantom Omni kinematics
Phantom Omni

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phantom omni

link lengths
phantom omni

End-Effector

a) l_2

θ_2

l_1

θ_1

Base

θ_3

Rear

Front

b) l_2

θ_2

l_1

θ_1

Base

θ_3

Rear

Front

c) l_2

θ_2

l_1

θ_1

Base

θ_3

Rear

Front

singular configurations
phantom omni

If $\theta_3$ is fixed, we can regard this as a two-link manipulator. When $\theta_3 = 0$, on the $y - z$ plane,

$$\begin{bmatrix} y \\ z \end{bmatrix} = \begin{bmatrix} l_1 \sin \theta_1 + l_2 \sin \theta_2 \\ l_1 \cos \theta_1 + l_2 \cos \theta_2 \end{bmatrix}$$

Now, let us consider $\theta_3$. Note that $\theta_3$ affects $x$ and $z$ position, but not $y$ position. So, we first calculate a link length, $L$, on the $z - x$ plane:

$$L = l_1 \cos \theta_1 + l_2 \cos \theta_2$$

(1)

Then, rotating the link length $L$ around the $y$-axis gives you the forward kinematics of an Omni:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} L \sin \theta_3 \\ l_1 \sin \theta_1 + l_2 \sin \theta_2 \\ L \cos \theta_3 \end{bmatrix} = \begin{bmatrix} (l_1 \cos \theta_1 + l_2 \cos \theta_2) \sin \theta_3 \\ l_1 \sin \theta_1 + l_2 \sin \theta_2 \\ (l_1 \cos \theta_1 + l_2 \cos \theta_2) \cos \theta_3 \end{bmatrix}$$
phantom omni

By definition, Jacobian matrix for the Omni is

\[
J = \begin{bmatrix}
\frac{\partial x}{\partial \theta_1} & \frac{\partial x}{\partial \theta_2} & \frac{\partial x}{\partial \theta_3} \\
\frac{\partial y}{\partial \theta_1} & \frac{\partial y}{\partial \theta_2} & \frac{\partial y}{\partial \theta_3} \\
\frac{\partial z}{\partial \theta_1} & \frac{\partial z}{\partial \theta_2} & \frac{\partial z}{\partial \theta_3}
\end{bmatrix}
\]

\[
= \begin{bmatrix}
-l_1 \sin \theta_1 \sin \theta_3 & -l_2 \sin \theta_2 \sin \theta_3 & (l_1 \cos \theta_1 + l_2 \cos \theta_2) \cos \theta_3 \\
l_1 \cos \theta_1 & l_2 \cos \theta_2 & 0 \\
-l_1 \sin \theta_1 \cos \theta_3 & -l_2 \sin \theta_2 \cos \theta_3 & -(l_1 \cos \theta_1 + l_2 \cos \theta_2) \sin \theta_3
\end{bmatrix}
\]
Assume the device currently has joint angles $\theta = [45^\circ \ -45^\circ \ 0^\circ]^T$, which is near the center of its workspace. If the joint velocities are $\dot{\theta} = [180 \ 90 \ 0]^T$ degrees per second, what is the vector of Cartesian endpoint velocities?

Computing the cartesian endpoint velocities is straightforward using the Jacobian and the joint velocities. The joint velocities must first be converted into rad/s.

$$
\begin{bmatrix}
\dot{x} \\
\dot{y} \\
\dot{z}
\end{bmatrix} = J \dot{\theta}
$$

$$
= J \begin{bmatrix}
\pi \\
\frac{\pi}{2} \\
0
\end{bmatrix}
$$

$$
= \begin{bmatrix}
0.00 \\
0.44 \\
-0.15
\end{bmatrix} \text{ [m/s]}
$$
phantom omni

Suppose that you want the robot end-effector to push on tissue with a Cartesian force vector of $F = [4 \ 1 \ 3]^T$ N. Your device is at the same position as stated above. What vector of joint torques would be needed to create this force at the end-effector?

You can calculate joint torques from Jacobian matrix and Cartesian force:

$$\tau = J^T F$$

$$= \begin{bmatrix} -0.19 \\ 0.37 \\ 0.75 \end{bmatrix} \text{[N-m]}$$

Note that this assumes that all the energy generated from the motors would equal the work done by the end effector, that is, there is no energy loss.
pantograph mechanism
Definition 1: a mechanical linkage connected in a manner based on parallelograms so that the movement of one pen, in tracing an image, produces identical movements in a second pen.

Definition 2: a kind of structure that can compress or extend like an accordion
pantograph haptic device

Xiyang Yeh, ME 327 2012
http://charm.stanford.edu/ME327/Xiyang
pantograph haptic device

Sam Schorr and Jared Muirhead, ME 327 2012
http://charm.stanford.edu/ME327/JaredAndSam
The Pantograph Mk-II: A Haptic Instrument

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Abstract—We describe the redesign and the performance evaluation of a high-performance haptic device system called the Pantograph. The device is based on a two degree-of-freedom parallel mechanism which was designed for optimized dynamic performance, but which also is well kinematically conditioned. The results show that the system is capable of producing accurate tactile signals in the DC–400 Hz range and can resolve displacements of the order of 10\(\mu\)m. Future improvements are discussed.


I. INTRODUCTION

The scientific study of touch, the design of computational methods to synthesize tactile signals, studies in the control of haptic interfaces, the development of force-reflecting virtual environments, and other activities, all require the availability of devices that can produce reliable haptic interaction signals. In some cases, it is needed to produce well controlled stimuli. In other cases, it is important to have the knowledge of the structural dynamics of a device, but in all cases, these activities entail having devices which are well characterized.

Following SensAble's Phantom and Immersion's Impulse Engine, several new commercially-available general-purpose haptic devices have been recently introduced: MPB's Freedom-6S, Force Dimension's Omega, Haption's Virtuose, Immersion Canada's PenCat/Pro; plus other application-specific devices. In addition, interesting, low-complexity, high-performance devices have also become available, either from research institutions or from commercial sources [9], [10], [15], [21]. We felt, nonetheless, that a general-purpose laboratory system having high performance features, would be a valuable tool.

With this in mind, we set out to redesign the 'Pantograph' haptic device, first demonstrated at the 1994 ACM SIGCHI conference in Boston, MA [22]. Our first goal was the creation of an open architecture system which could be easily replicated from blueprints and from a list of off-the-shelf components. The second goal was to obtain a system which would have superior and known performance characteristics so that it could be used as a scientific instrument. Our intention is to make the system available in open-source, hardware and software.

An important aspect of the Pantograph, a planar parallel mechanism (Fig. 1d), is the nature of its interface: a non-slip plate on which the fingerpad rests (Fig. 1e). Judiciously programmed tangential interaction forces \(f_T\) at the interface (Fig. 1e) have the effect of causing fingertip deformations and tactile sensations that resemble exploring real surfaces.

\(\begin{align*}
\text{Encoders} & \quad \text{Torquers} \\
\text{Interface Plate} & \quad \text{Accelerometer (optional)} \\
\text{Load Cell} & 
\end{align*}\)

Fig. 1. Pantograph Mk II electromechanical hardware. (a) Side view showing the main electromechanical components. (b) Front view. (c) Photograph. (d) Top view of the five-bar mechanism and plate constrained to 2-DOF. (e) The interaction force has two components: \(f_N\) is measured by the load cell and \(f_T\) results from coupling the finger tip to the actuators via linkages.

Campion and Hayward, IROS 2005

http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1545066
example

Find the forward kinematics
Find the Jacobian
rendering
a commercial 3-DOF device

2014 slides from Francois Conti about Force Dimension and the Novint Falcon
Designing Commercial Haptic Devices

ME 327
05/09/2014

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Commercial Haptic Devices

A 10 Year Journey
3D Consumer Haptic Interfaces

Design Challenges

omega.3
$20'000

Falcon
$200
3D Consumer Haptic Interfaces

Design Challenges

Maxon Motor
$150

Johnson Motor
$1.50
Position Sensors

Optical Encoders

- **Resolution**
  1000 increments per revolution.

- **Low signal noise**
  Signal remains digital. No analog conversion.

- **Contact**
  Frictionless. No contact between optical disc and sensor.

- **Cost**
  30-40 US$ for an encoder and counter.

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Phantom
Sensible Technologies
Position Sensors

Optical Encoders
Position Sensors

Optical Encoders
Mechanical Design

Articulated Systems
Communication Interface

Information Transfer

position sensing

actuation

force output

information transfer

receiving position data

computing forces
Computation

Position and Force

Joint space position

Cartesian position

Motors torques

Force computation

\[ \tau = J^T F \]
Actuation Stage

Current Amplifiers

digital to analog signal conversion  
torque / force commands

current amplifier
Product Creation

Designing Prototypes

Prototype
Force Dimension, Lunar Design
Product Creation
Designing Prototypes
Product Creation
Industrial Design

Falcon
Novint Technologies, Force Dimension
Product Creation

Industrial Design
Product Creation

Industrial Design
Product Creation

Industrial Design
Product Creation

First Production
Product Creation

Launching the Product
Patents
Protecting Ideas

Kinematic chain with an arm comprising a curved portion and parallel kinematics transmission structure with such kinematic chains

A kinematics chain (6) for a device for transmitting movements comprising a parallel kinematics transmission structure providing three degrees of freedom, the parallel kinematics transmission structure comprising a base member (2) and a moveable member (4), the kinematics chain (6) comprising a first arm (8) adapted to be coupled to the base member (2) and comprising a curved portion (52).
Medical Applications
High-End Interfaces
Medical Applications

Building Partnerships

Sensei
Hansen Medical, Force Dimension
Haptics

The Sense of Touch
Haptic Devices
Market and Applications

Cybergrasp
Virtual Technologies

iDrive
Immersion Corporation

Phantom
MIT / Sensable Technologies

Haptic Workstation
Immersion
Le Syntaxeur
EPFL – Ecole Polytechnique Fédérale de Lausanne

Le Syntaxeur
EPFL, Switzerland
Creating a Company
Designing and Manufacturing Haptic Devices

Force Dimension
Switzerland