**Intelligent Assist Devices**

- IADs use computer control of motion to create functionality greater than that of conventional ergonomic assist devices, such as hoists, overhead rail systems, and manual manipulators.

**Two forms of intelligent assist**

- **Power Assist**
  - to augment operator-applied forces
  - necessary to counteract gravity
  - improves ergonomics by reducing stress on operator

- **Guidance (Virtual Surfaces)**
  - virtual surfaces guide the motion of payload/worker
  - allows physical interface to computer: co-manipulation
  - analogy: straightedge vs. freehand

**Co-Manipulation with Virtual Surfaces**

- In co-manipulation tasks, a human and robot *share* control

**Example of Virtual Surfaces: the “virtual funnel”**

**Advantages of Virtual Surfaces**

- **Ergonomics**
  - pushing straight is easier than redirecting; virtual surface takes care of redirecting

- **Quality/Productivity**
  - virtual paths or virtual funnels ensure that collisions do not occur
  - motion along a virtual surface is swift and sure

- **Flexibility**
  - virtual surfaces are programmable, allowing for worker preferences, product mix, inexpensive retooling…

- **Software Driven Material Handling**
  - due to programmability, virtual surfaces can be interfaced to larger-scale (e.g., plant-wide) information systems
Technologies for implementing virtual surfaces

- Powered manipulators
  - servo-actuated joints
  - excellent for power assist
  - poor for virtual surfaces
- Cobotic manipulators
  - servo-steered joints
  - completely passive (no power assist)
  - excellent for virtual surfaces
- Powered cobotic manipulators
  - a single servo-actuated joint, multiple servo-steered joints
  - excellent for both power assist and virtual surfaces

Cobots

- Cobots implement virtual surfaces via "servo-steered" joints
- Cobotic surfaces are programmable, passive, smooth and hard

Two basic control modes of cobots

- Free mode
  - cobot is responsive to the operator, steering to allow whatever direction of motion the operator intends
- Path mode
  - cobot is unresponsive to the operator, but instead steers to remain on a virtual surface defined in software

Cobots have more generalized coordinates than degrees of freedom

- Wheel is a continuously variable transmission (CVT). The ratio of x velocity to y velocity is set by steering angle $\theta$
- Unicycle Cobot has one degree-of-freedom, but two generalized coordinates

The “virtual caster” -- adding degrees of freedom

- Feedback control can be used to make the unicycle cobot behave as though it had two degrees-of-freedom
- Lateral force and velocity are measured, and wheel is steered to minimize lateral force

Free mode or “virtual caster”

- $\omega_s$ is angular velocity of steering: this is under our control
- Use coordinate system aligned with instantaneous rolling direction: $F_\perp v_\perp a_\perp F_\parallel v_\parallel a_\parallel$
- In the rolling direction $F_\parallel = m a_\parallel$ is natural and not under our control
- Match it in the perp direction via active control:
  - have $a_\perp = \omega_s v_\parallel$; want $F_\perp = m a_\perp$
  - so use control law $\omega_s = F_\perp / m v_\parallel$
Path mode

• \( \omega_s \) is angular velocity of steering: this is under our control
• \( v_l \) is rolling velocity, not under our control
• \( \rho \) is local curvature of path to be followed
• Use control law \( \omega_s = \frac{v_l}{\rho} \)
  (open loop control; feedback terms are more complicated)

Inherently passive

• Although a servo motor is used to steer the wheel of the Unicycle Cobot, none of the power introduced by this motor may be coupled into the plane of motion.
  ● Thus, the cobot is completely passive from the operator’s perspective.

Beyond unicycles

• Regardless of configuration space dimension \( n \), all cobots have one degree-of-freedom
  – under feedback control, the apparent dof can vary from 0 to \( n \)
• Cobot singularities are configurations in which a degree-of-freedom is \textit{gained}
• All cobots rely upon steerable nonholonomic devices
  – steerable wheels are best suited to low dimensional, parallel cobots
  – a “rotational CVT” has been developed which is well-suited to higher dimensional, serial cobots

Cobot characteristics

• Steering motors cannot initiate cobot motion; operator pushing cannot affect steering
• No kinetic energy source except human muscle >> safety
• Smooth, hard, frictionless constraint surfaces — so you can slide along them \textit{without loss of energy}
  – important if you want to interact with the constraints (use them for your benefit) rather than just avoid them
  – optimally, a collision with a surface should redirect kinetic energy, not absorb it.
• Small actuators control large forces

Scooter: a tricycle cobot

• Floor-based
• Three independently steered wheels
• Three dimensional workspace \((x, y, \theta)\)

How to Build a Serial, Revolute Cobot

• Remove the actuators from a serial robot
• Couple the \( n \) revolute joints using \( n-1 \) steerable nonholonomic devices, reducing the degrees-of-freedom to 1
  – e.g. 3 revolute joints coupled by 2 nonholonomic devices:
Beyond wheels: the spherical CVT

- Suppose we wanted to build a serial link cobot... what would be the appropriate servo-steered device to couple the joints?
- Key point: the joints are rotary

A servo-steered device to couple rotary motions is...

\[
\frac{\omega_1}{\omega_2} = \tan(\alpha)
\]

A unicycle wheel relates two translational velocities

\[
\frac{v_x}{v_y} = \tan(\alpha)
\]

The needed device relates two angular velocities

...is a continuously variable transmission

\[
\omega_1 = V_x, \omega_2 = V_y
\]

Allow the plane under the unicycle wheel to move, and convert translational velocities to rotational

\[
\frac{\omega_2}{\omega_1} = \tan(\alpha)
\]

Wrap the plane into a sphere

CVT - “the revolute analog of a rolling wheel”

A serial link cobot

- This mechanism looks quite different than Scooter... ...but has essentially the same capabilities.

Powered cobots

- All power derives from a single actuator, regardless of number of degrees of freedom
- Virtual surfaces are implemented by servo-steered joints, just as with passive cobots
- Power assist and virtual surface functions are completely decoupled
Applications

- Software guided materials handling, e.g. in automotive assembly
- Haptic display of CAD models, e.g. in product design
- Rehabilitation and exercise machines
- Guidance in computer assisted surgery
- Others :)

Research areas

- Path planning: a traditional area, now with a human operator and with guiding surfaces rather than trajectories
- Haptic effects: attractive surfaces, breakthrough strengths, etc.
- Higher dimensions: path tracking becomes quite non-trivial beyond the single wheel
- Control: new control issues arise from the central role played by the human; neither a “disturbance” nor an “input”
- Mechanics of CVTs

Summary

- Materials handling industry moving towards “software driven materials handling”
- Virtual surfaces can form the interface between computers and people, in the control of motion
- Cobots implement smooth hard virtual surfaces, safely

Thanks to...

- General Motors Foundation
- General Motors
- Ford Motor Company
- National Science Foundation

For more information, phone numbers, etc: http://cobot.com